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EFFECTS OF THERMAL STRESS ON HUMAN PERFORMANCE: A REVIEW AND CRITIQUE OF EXISTING METHODOLOGY

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ABSTRACT

A critical review of the literature provides the basis for an analysis of the effects of thermal stress on human performance. Research in this area to date reflects a wide divergence of opinion regarding the magnitude, direction and significance of performance changes occurring under conditions of high temperature, humidity, solar radiation, etc. An attempt to resolve major conflicts in experimental findings leads to a detailed examination of such factors as thermal stress indices, exposure times and acclimatization. The role of the subject in thermal stress research is discussed with emphasis on the contribution of such psychological variables as personality and motivation to performance change. Recommendations for future research are advanced.

CONTENTS

APPENDIXES

FIGURES

TABLES

EFFECTS OF THERMAL STRESS ON HUMAN PERFORMANCE:

A REVIEW AND CRITIQUE OF EXISTING METHODOLOGY

INTRODUCTION

Recent reports from Southeast Asia indicate that Army aviators are experiencing difficulties due to heat stress induced by high cockpit operating temperatures. As reported, these difficulties are primarily physiological in nature. Crews flying the fixed wing OV-1 (MOHAWK) have complained of discomfort, fatigue, and other symptoms indicative of mild heat exhaustion (Joy, 1967). Anderson (1967), describing the effects of cockpit temperatures on the pilot/copilot in the rotary wing AH-1G (HUEYCOBRA), does not list specific complaints but comments:

> "Suffice to say that it greatly reduces pilot proficiency during extended periods of flight while exposed to direct sunlight. (Especially in the hot dry season.) Pilots are hindered by perspiration (restricting vision) and a feeling of exhaustion and dehydration after extended periods of operation." [p. 16]

The alleviation or removal of such physiological symptoms has been attempted using a variety of techniques including air conditioning, artificial acclimatization (Allan, 1965), caloric neutralization (Gold, 1965), drugs (Goldsmith, Fox & Hampton, 1966) and modification of clothing and ventilation specifications (Joy, 1967). All of these approaches have proved effective to some extent. With the exception of air conditioning, however, all are based on what Connell (1948) has termed the "Concept of Physiological Adequacy" which assumes that behavior will remain normal as long as thermal equilibrium can be maintained. The evidence in support of this assumption derives almost exclusively from studies of heavy physical labor and/or brief exposures to extremely high temperatures and humidities. In the context of determining maximum physiological tolerance times, it has proven useful; but when applied to the performance of pilots flying under conditions of high cockpit heat loads, the validity of the assumption becomes questionable. Flying is a continuous, complex task which demands a high degree of speed, accuracy and coordination of responses, but requires little in the way of sustained, intense physical labor. Previous attempts to establish permissible upper limits for cockpit temperatures have relied heavily on subjective evaluations of comfort or on physiological adequacy alone, and have tended to ignore the following facts pointed out by Blockley, McCutchan and Lyman (1954):

> "...studies of unclothed men in relatively mild heat conditions, within the climatic range, have shown that the ability to perform even simple tasks is impaired long before the danger of physiological collapse is apparent. Basically, the assessment of body heat storage is predictive of the physiological tolerance of men; it is much more difficult to predict the way in which performance will be affected by the discomfort which accompanies even a perfect physiological adjustment to heat stress. Psychological consideration become of supreme importance in this mild heat area." [p. G-1]

Past reliance on the concept of physiological adequacy has specifically resulted in a failure to investigate the effects of heat on such components of piloting as memory, complex problem solving, decision making and complex (time-shared) psychomotor activity. Because of the lack of systematic data in these areas, there currently exists no reliable set of criteria for the design and evaluation of crew station thermal environments as they affect performance. Even in instances in

which there has been a firm decision to air condition, the lack of well-defined levels of acceptable pilot performance under varying heat conditions proved a major hindrance in selecting equipment under the restrictions imposed by aircraft weight and power limitations. As Blockley et al (1954) noted:

> ". .there is a basic conflict between the requirements for pilot comfort and survival and aircraft performance. Since the latter may well be a critical factor in completing a successful mission or in overcoming the enemy in a combat maneuver, it is evident that pilot effectiveness and safety is concerned in either instance. There is here no simple issue of man versus machine, such as guides the philosphy of industrial hygiene. The biotechnical goal must be equally and coordinately to optimize both the cockpit environment and the aircraft performance. Both man and machine must be fit to fly successfully under the exigencies of modern air warfare." [p. viii]

In addition to providing design standards for maximally efficient environmental control systems (ECS), accurate and objective data on pilot performance under thermal stress is vital for predicting the magnitude, duration and significance of performance decrements, as they relate to mission requirements, in the event of ECS failure.

The type of performance data described above is of particular importance to the Army with respect to its wide-spread and increasing use of rotary-wing aircraft. These aircraft are frequently used to provide low-level visual reconnaissance and/or tactical fire support in conjunction with ground operations. As such, they are characteristically equipped with high-visibility canopies which increase pilot exposure to the effects of both direct and reflected solar radiation. Since such aircraft are currently operating at altitudes of 50-100 feet, under conditions of high ambient temperatures and humidities, the "greenhouse" effect produced by such solar radiation makes a major contribution to cockpit heat loads. Other sources such as (a) waste heat from power plants, weapons systems and avionics; and (b) inefficient or defective ventilation systems add to the heat stress imposed on the pilot. The heat stress from these combined sources poses a greater potential threat to helicopter pilots because:

> "The task of flying a helicopter is a complex one for two reasons. First, the vehicle has no inherent aerodynamic stability in any axis. It differs markedly from fixed wing aircraft in this respect. The pilot must fly the airplane at all times; "hands off" operation in rotor-craft is . . . neither easy nor safe. Second, the wide range of operating airspeeds demands a variety of flying techniques." (Billings, Eggspuehler, Gerke, & Chase, 1968, p. 19)

In summary, the following conditions have been outlined:

a. There are reports of heat stress from helicopter pilots.

b. The design of such craft and the climatic area in which they are deployed serve to increase cockpit operating temperatures.

c. These higher temperatures can affect pilot performance.

d. Decrements in performance are capable of producing greater effects in helicopters than in fixed-wing aircraft.

e. The Army is expanding its use of helicopters.

These factors, together with the reported mean flying times for such aircraft -- 160 hours/month -- argue strongly for the need to develop what Blockley, et al, (1954) termed ". . . a concept of physiological and performance effectiveness, evaluated by experiment under thermal conditions that lie far outside the comfort zone." [p. viii]

OBJECTIVE

The objectives of this paper are (a) to provide a comprehensive, critical review of the available literature on the effects of thermal stress on human performance; (b) to determine the extent to which experimental findings provide a consensus upon which to base design standards for crew station thermal environments; (c) to examine in detail those environmental and subject (S) variables which, when poorly controlled or differentially administered, have contributed to conflicting experimental results; and (d) to advance suggestions and recommendations based on the literature review and ancillary data for improving future research.

METHOD

Much of the work on the effects of thermal stress on performance has been done with the aim of improving various crew station environments. An analysis of this body of data provides the basis for subsequent discussions with respect to the role of environmental (indices of stress, exposure times) and subject (physiological-psychological adaptations) variables. Given the current status of research in thermal stress; viz., numerous conflicting reports regarding the effects on performance, an analytic approach is needed to identify relevant variables and assess their impact on future research.

EFFECTS OF THERMAL STRESS ON HUMAN PERFORMANCE

As Kaufman (1963) points out, heat has long been acknowledged as an important environmental stressor. The following review indicates, however, that there remain many areas of controversy with respect to its exact effects on human performance (see summary in Appendix A).

There are a number of bibliographies and reviews available on this subject (Bell & Provins, 1962; Groth & Lyman, 1963; Hendler, 1963; Stevenson & Johnson, 1967; Stevenson & Trygg, 1966; U. S. Army Tropical Test Center, 1967; Wing & Touchstone, 1963). Unfortunately, despite their publication dates, none of these compilations are recent or inclusive enough to allow an accurate appraisal of the effects of thermal stress on complex "mental" or psychomotor performance. The only recent review in this area was done by Wing (1965). He examined 15 experiments to determine the upper limits of "unimpaired mental performance." Since his goal was to plot performance decrement as a function of exposure times, however, the experiments chosen were necessarily limited to those in which some decrement was, in fact, reported. The major objection to such a procedure is that it tends to ignore or minimize the existence of studies which report no change (or, in some instances, improvements) in performance as a result of

exposure to high ambient temperatures. It is important that such divergent results be clearly acknowledged. Only then can comparisons be made with respect to experimental designs, apparatus, subjects, etc. Such comparisons are necessary not only in reconciling conflicting data, but also in establishing a reliable basis for the selection and/ or control of relevant variables in future work.

Reilly & Parker (1967a) have noted that "In comparing stress vs. nonstress performance in a given task, only three outcomes are possible: (1) improvement, (2) decrement, or (3) no change (p. 16)." Within each of these categories, studies included in the present review are further classified according to the type of performance investigated. These performance areas are similar to those used by Wing & Touchstone (1963), and include the following: (1) sensory thresholds and reaction time, (2) vigilance and perception, (3) psychomotor performance, and (4) "mental" performance. These categories are neither mutually exclusive nor exhaustive; they are primarily for convenience and represent only one of a number of possible classification systems. Finally, throughout the review the following abbreviations are used: DB = dry bulb, WB = wet bulb, RH = relative humidity, and ET = effective temperature. Dry and wet bulb temperatures will always be in that order and in this format: 85/69. In addition, unless otherwise specified, all temperatures reported are in degrees Fahrenheit -- this includes effective temperature which is based on the combined dry bulb/wet bulb readings corrected for air movement according to an empirically derived comfort scale (Houghton & Yaglou, 1932).

Improvement

Simple reaction time (SRT) to visual stimulation was found to decrease during a 210-minute exposure to conditions of 125.6 DB and 40 percent RH (Lovingood, Blyth, Peacock & Lindsay, 1967). Similar findings for SRT are reported by Reilly & Parker (1967a), who tested Ss twice during a six-hour exposure to temperatures of 98-102 DB and 76-84 WB.

Vigilance and preception were demonstrated by Reilly & Parker (1967a) to improve under heat stimulation as measured by S's responses to tasks measuring spatial orientation, visual reaction time, and perceptual speed. Poulton & Kerslake (1965) noted significantly better performance in both auditory and visual vigilance tasks at an ET of 86°. Wilkenson et al (1964) also showed that auditory vigilance improved for both number of signals heard and response-to-signal reaction times, when S's body temperatures were raised to 101.3°.

Psychomotor performance has been shown to improve under thermal stress for such tasks as mirror tracing, wrist-finger speed (Reilly & Parker, 1967), and rapid line drawing (Vaughan, Higgins & Funkhouser, 1968). Lovingood et al (1967) noted significant facilitation of percision work with small objects.

At present there are few reports of complex "mental" performance (involving such processes as memory or judgment) being in any way enhanced under conditions of high ambient temperatures. Lovingood et al (1967) did note that under heat Ss attempted significantly more mental arithmetic (simple addition) problems.

No Change

Both simple and serial reaction times have been studied under conditions of high body and ambient temperatures (Ivy, 1945; Pace, Fisher, Bieen, Pitts, White, Consolozio & Pecora, 1945; Pace, White, Fisher & Birren, 1946). Coakley (1948), having reviewed this work and 12 other studies dealing with choice, visual reaction times and auditory reaction times, concluded that: "Under the conditions of these studies, there is no significant variation of reaction time with ambient temperatures up to 117° DB, 85° WB (p. 21)." Peacock (1956) was also unable to demonstrate any adverse effects of heat on serial reaction times.

Loeb et al (1956), exposing Ss to noise, heat and vibration, found that heat alone, ranging from 105° to 125° DB, produced no significant effects on a visual vigilance task involving the detection of changes in pointer alignment on a clock face and a set of 20 dials. Carlson (1961), theorizing that environmental and task inputs sum to provide operator overload and stress, found a "trend" toward decrement in visual vigilance at temperatures between 104° and 122° DB; but the trend failed to achieve statistical significance. Using the criterion of the proportion of signals missed to signals given, Bell, Provings & Hiorns (1964) tested Ss at temperatures from 85°/76° to 145°/117° and found no significant decrements in either auditory or visual vigilance. Fine, Cohen & Crist (1960), using a 6 1/2-hour exposure time at temperatures of 70°/53°, 70°/68°, 95°/ 70.5° and 95°/92°, found ". . . no increment or decrement in performance . . . that could be attributed to either high temperature or high humidity (p. iv)" for an auditory discrimination task.

The previously cited study by Reilly & Parker (1967a) is one of the most comprehensive examinations of both simple and complex psychomotor performance under heat stress. A battery of 16 tests was developed based on an extensive review of the literature and a detailed examination of the techniques of analog simulation (Parker, 1964; Reilly & Parker, 1967b). Ten of the tests cover such general areas as muscular control, eye-hand coordination, and pursuit or compensatory tracking. As experimental temperatures over the six-hour exposure period from 98°/76° to 102°/84°, two testing periods failed to show performance decrements for the following tasks: arm-hand steadiness, finger dexterity, manual dexterity, speed-of-arm movement, multilimb coordination, control precision and position reproduction (pursuit tracking), rate and acceleration control (compensatory tracking), and movement analysis. An earlier study by Russell (1957) also reported no change in pursuit tracking under heat. The work of Lovingood et al (1967) corroborates the non-significant findings with regard to arm-hand coordination, and Vaughan et al (1968) failed to note decrement in hand-finger dexterity at 115° DB, RH 43.

A number of studies have reported no significant changes in "mental" performance as a function of heat stress. Bartlett & Gronow (1955) presented Ss with a number of cards each containing symbols representing aircraft; the "aircraft" were to be perceived as "moving" according to a set of rules similar to those governing chess pieces. Subjects were required to decide how many, if any, "collisions" would occur, the "aircraft" involved, and the site of collision. Using 60-70° as a control, Ss were exposed to 80°/70°, 90°/80° and 100°/90° experimental conditions. The results indicated that " . . . there was no important effect due to heat level . . . (p. 1)." Mayo (1955) compared test scores for two groups of students in a Navy electronics course lasting one month. One group studied in an air-conditioned room, the other in quarters heated by the summer sun. No significant differences in test scores were found. Two experiments were presented by Chiles (1957, 1958) in an attempt to replicate earlier findings reported by Pepler. The tast used in both experiments (developed by Mackworth in 1946) required Ss to compare each of 20 moving cards with each of 10 stationary cards to determine differences in position of a set of six symbols which appeared in varying arrangements on all cards. Experimental temperatures in Experiment 1 were 85°/75°, 90°/80°, 95°/85° and

$100^{o}/90^{o}$; in Experiment 2 they were $85^{o}/75^{o}$, $90^{o}/80$ $^{11}0^{o}/90^{o}$ and $120^{o}/90^{o}$. Chiles (1958) concluded that "In both experiments, differences in performance among the temperature conditions were small and not significant (p.89." Fine et al (1960) examined the effects of high and low humidity as well as high ambient temperatures on the solution of anagrams. Testing Ss immediately after entering and just prior to leaving the experimental situation, they found no evidence of increment or decrement in performance. Finally, Givoni & Rim (1962) used a two-hour exposure to a 109^{o} DB, - 40 percent RH environment and reported no changes in the ability to perform five-digit multiplication, in I.Q. test scores, or in paper and pencil measures of emotional stability.

Decrement

Decrements in tactile sensitivity have been found to occur at temperatures higher than 86^{o} DB (Russell, 1957). Serial reaction times showed a small but statistically significant increase in a study by Fraser & Jackson (1955); they concluded that reaction time " . . . offers a clear-cut index of psychomotor change . . . (p. 976)" under conditions of heat stress ranging from 90^{o} to 104^{o} DB with 90-95 percent satuation.

The first intensive investigation of temperature effects on auditory and visual vigilance was done by Mackworth (1946b). Using partially clad, artifically acclimatized Ss, he demonstrated a significant increase in the number of visual signals missed at temperatures above and below an "optimum" point of $85^{o}/75^{o}$, - ET 79^{o}. Auditory vigilance was tested by Ss receiving morse code messages; the percentage of faulty messages increased across the ET range $79\text{-}97^{o}$ (Mackworth, 1946a). Working with naturally acclimatized Ss in Singapore, Pepler (1953) attempted to replicate Mackworth's findings and, in general, was able to do so. He reported that error scores in both visual watch-keeping (Clock Test) and Morse code reception increased between 81^{o} and 86^{o} ET (Pepler, 1958). Bursill (1958), using peripherally presented visual stimuli in conjunction with a continuous, centrally displayed tracking task, found that at $105^{o}/95^{o}$ ". . . there is a tendency for the field of awareness to be funneled towards the center. Signals presented at greater eccentric angles have a higher probability of being missed in the hotter conditions (p. 113)."

Studies of psychomotor performance under heat have relied heavily on some variation of pursuit tracking as the dependent variable. Again, the early work done by Mackworth (1945, 1961), who found for the pursuitmeter task ". . . the effective temperature of 86^{o} was the crucial point at which performance definitely began to deteriorate . . . (p. 195)." Pepler (1953, 1958, 1960), in a series of experiments, reported essentially similar results except for placing the point of initial decrement somewhere between ETs of 81^{o} and 86^{o}; his studies also indicated that heat affects both pointer alignment and the number of movements used in tracking. In response to a conflicting report by Blockley & Lyman (1951), Pepler later exposed Ss to a temperature of $116^{o}/105^{o}$ and again demonstrated severe decrements in psychomotor performance (Pepler, 1959). The study by Blockley & Lyman (1951) is itself of some interest, since it constitutes one of the few efforts directly relevant to pilot performance under thermal stress. Using 80^{o} DB as a control temperature, they tested the ability of experienced pilots to fly standard "flight" patterns in an aircraft simulator under temperatures of 160^{o}, 210^{o} and 235^{o} DB (20-30 percent RH)' They concluded that:

"Though differing in level of competency or skill in the task, no subjects showed a change in proficiency within 80 minutes of "flight" in the comfortable environments, but under heat exposure showed marked deterioration of performance in the terminal stages, commencing from four to thirteen minutes prior to the termination of exposure. The amount of deterioration, i.e., the increase in error per four minute cycle of the flight pattern, was greater in the high temperature exposures than at 160° F. At 200° and 235° F the deterioration was markedly greater and began sooner from the two less competent subjects (p. iii)."

The piloting task used requires almost continuous scanning of instruments, and the fact that such "time-sharing" behavior is susceptible to heat stress is confirmed to some extent by the findings of Reilly & Parker (1967a). They found decrements in performance in a time-sharing task and also in a task requiring Ss to predict the position of a target which disappeared at random intervals during its progress across a CRT tube. Rotary pursuit tracking was studied by Teichner & Wehrkamp (1954) using exposure times of 25 minutes with five-minute test periods. Controlling for fatigue effects, they found time-on-target scores were significantly poorer at temperatures above and below 70° DB. Finally, Pepler (1960) investigated the differential effects of warmth, glare and a background of quiet speech on pursuitmeter performance. He found that heat significantly increased the number of pointer movements (corrections) made and decreased overall accuracy.

Using the "complex mental task" previously described in the studies by Chiles in the "No Change" section, Pepler (1958) varied speed of presentation and ET (76, 81, 86 and 90°) and found once again that the least number of comparisons were missed at an ET of 81°; at the slower speed of presentation, more omissions were made under the hot conditions. In a study designed to determine the effect of high ambient temperature on ability to recall aurally presented messages, Wing & Touchstone (1965) exposed Ss for one hour to ETs of 72, 90 and 95°. Subjects worked continuously during the session, and "The results showed that average recall dropped significantly as environmental temperature was increased. The recall decrement between 90° and 95° F was statistically significant, but the drop in recall between 72° and 90° was not significant. Messages of all types suffered approximately equal decrements under high temperatures (p. iii)."

Whether or not they can be said to validly represent complex "mental" activity, such tasks as simple addition and number checking have been shown to be affected by thermal stress. Performance decrements for these kinds of tasks have been observed under conditions of high ambient temperature (Blockley & Lyman, 1950) as well as situations involving raised body temperature only (Whilkinson et al, 1964). Finally, there are a number of studies (Fox, Bradbury, Hampton & Legg, 1967; Bell, 1965; Kleber, Lhamon & Goldstone, 1963) which suggest that even the subjective perception of time may change as a function of increased body temperature. Fox et al. found that ". . . despite large individual variations, group mean- time judgments shortened (i.e., the internal clock speeded up) as body temperature increased." (p. 88)

THE CONCEPT OF "THERMAL STRESS"

Beginning with the title, the term "thermal stress" appears frequently throughout this paper. Because the conceptualization of any phenomenon strongly influences subsequent research, it is necessary, at this point, to examine the various definitions of thermal stress. Basically, there are three:

1. Thermal stress is a set of environmental parameters (dry bulb and wet bulb temperatures, air velocity, radiant energy, etc.) whose values either (a) exceed some subjectively determined "comfort level" or (b) lie at the extremes of some empirically determined climatic probability curve.

2. Thermal stress is a set of quantified physiological responses whose values lie outside those established as "normal" under "comfortable" environmental conditions.

3. Thermal stress is a condition generated within an organism through exposure to high levels of heat and humidity and is evidenced by the organism's "abnormal" physiological responses.

It is obvious that definitions one and two actually constitute a single operational definition of thermal stress. There is a difficulty here, however, in dealing with the hypothetical conditional statement implied by the definition, viz.,

> If abnormal physiological responses are present, then the environmental parameters used constitute a thermal stress condition.

As long as the rules of logic are observed, there can be no formal objection to this "if-then" formulation. Two errors of logic, however, are frequently committed, and both can lead to the type of situation found in the literature review.

The first error, denying the antecedent, results in this conclusion:

If there are no abnormal physiological responses, then the organism has not been exposed to conditions constituting a thermal stress.

The second error, affirming the consequent, leads to this type of statement:

> If there are present certain values of environmental parameters, then the organism will exhibit abnormal physiological responses.

To avoid the above fallacies, the present author adopts the following definition of thermal stress:

> Thermal stress is an inferred state within the organism, occurring under those levels of temperature and humidity which are sufficient to produce a statistically significant decrement in the organism's ability to perform a specific task.

This definition embodies two of the major themes of this paper.

1. Conflicting reports in the literature on the effects of thermal stress on performance are due largely to a failure to agree upon values of heat and humidity which constitute a "thermal stress."

2. More emphasis should be placed on the effects of the thermal environment on psychological functioning as measured by performance on specific (and preferably complex) tasks.

Since the author's definition is provisional, in the remainder of the paper "thermal stress" can be nominally interpreted to refer to a set of environmental stimuli which include dry bulb and wet bulb temperatures, air velocity, etc. The goal remains, however, to shift from an emphasis on stress to a focus on strain as defined by performance decrement, regardless of the actual levels of the thermal environment. A further discussion of this subject appears in the Conclusions and Recommendations section.

SELECTION OF VARIABLES FOR FUTURE RESEARCH

Taken as a whole, the literature reviewed provides no clear-cut criteria upon which to base predictions of mental or psychomotor performance under thermal-stress conditions. The basic lack of agreement between the various studies is primarily the result of a generalized failure to standardize experimental conditions. The use of a wide variety of temperature levels, exposure times, etc., makes any direct comparisons of results difficult. The studies can, however, be profitably examined under the following assumption: if the application of differing levels (or the omission) of an experimental variable leads to conflicting conclusions regarding performance, then the effects of that variable must be controlled and accounted for in future research (see summary in Appendix B). In addition to specifying the parameters relevant to a general program of heat-stress research, the remainder of this paper provides some rationale for choosing specific levels of variables to be used in a future study. The factors to be considered are designated as environmental, or subject variables, and are evaluated, wherever possible, in terms of their independent effects on performance.

ENVIRONMENTAL VARIABLES

Indices of Stress

Much of the controversy regarding the effects of thermal stress stems from a failure to consider "heat" as a complex stimulus. Heat stress, as experienced by the human organism, is actually a result of the body's integration of the effects of (1) air temperature, (2) humidity, (3) air movement and (4) radiant heat. As Minard (1964) pointed out:

> "A comprehensive index of environmental heat stress must evaluate the four physical factors of the thermal environment in the proportion to which each will effect the exchanges of heat by radiation, convection and evaporation between the human body and its environment under varying conditions of skin temperature and skin wetness (p. 3).

The developmental history of attempts to construct such an index began with the use of wet

bulb temperature as the single explanatory factor (Bedford, 1961). The availability of increasingly accurate instruments and measurement techniques, in conjunction with subjective reports of thermal comfort, led to the subsequent inclusion of the remaining three factors (dry bulb temperature, air velocity, radiant heat). Usually, the addition of each new factor resulted in a newly titled index, and the proliferation of these indices is in part responsible for some of the difficulty in comparing studies of performance under heat stress. The terms "heat' or "high ambient temperatures" are frequently used by experimenters to refer to only one or two of the four components involved in the production of "stress." Many authors, for example, report experimental temperatures in terms of wet and dry bulb readings only, and give no information about air movement. Some studies list effective temperatures but provide no wet or dry bulb figures; others report dry bulb temperatures only, without reference to humidity. With the exception of Joy (1967), none of the studies previously reviewed attempted to assess the possible significance of radiant-heating effects. Because of a number of different thermal-stress indices are still being employed, a chronology of their development and a brief description of each is provided in Table 1. It should be noted that these indices are primarily concerned with the physiological impact of heat on man's ability to work, and in cases where a particular index value serves as a limiting factor for performance, it is generally physical performance which is being referred to. Descriptions of the indices are adapted from more detailed reports (ASHRAE Guide and Data Book, 1965-1966; Bedford, 1961; Hall & Polte, 1961; Minard, 1964).

In examining the various indices in Table 1 it becomes apparent that all are based, to some extent, on the previously described concept of physiological adequacy. As such, they are concerned with the metabolic heat loads generated by various thermal environments; these loads are usually assessed indirectly by the measurement of physiological parameters including heart rate, rectal and skin temperature, sweat rate, etc. Table 2 (Yaglou & Minard, 1957) provides an example of the relationship between the many indices and one such physiological measure. Unfortunately, correlation coefficients of this magnitude are seldom, if ever, obtained between performance and physiological responses.

With reference to the selection of a particular index for research in heat stress, the ASHRAE Guide and Data Book provides the following summary and recommendations:

> "There is presently no one proven method for combining all of the component heat loads into a single value that would accurately indicate the degree of heat stress as perceived by an individual working or resting in a hot environment. The difficulty lies in the inability to simulate human response. Physical instruments can accurately integrate, but the human body has the ability to differentiate between component thermal effects and to make prompt adaptive changes which the instruments cannot do. Nonetheless, each of the indices will supply valuable information on which to base an informed opinion. The index or indices selected for use should depend upon the nature and extent of the problem, the equipment and facilities at hand, and the availability of personnel trained in the field of thermal stress (p. 107)."

Since this advice is somewhat general, let me give an example of how one might go about selecting a specific stress index. In the process, problems of selection criteria will become apparent. I have chosen as an example the WBGT index. In a prospective study, the selection of this index could be substantiated as follows:

a. In the presence of a radiant-heat load, the globe temperature (GT) represents the balance between heat gained by radiation and heat lost by convection; in effect, it integrates radiant heat, air movement and air temperature into a single reading. This GT reading used in conjunction with a WB thermometer takes into account the four physical components of the thermal environment without requiring a separate measurement of air movement.

TABLE 1

Indices of Thermal Stress

Index	Date	Developed by	Description	Comments
- (effective temperature)	1923	Houghten & [illegible]	An empirical sensory index combining into a single value the thermal effect of temperature, humidity and air movement. Generated through repeated experiments in which subjective responses of groups to these factors were compared. Combinations of temperatures, humidities and velocities which produced the same feeling of warmth were assigned the same effective-temperature value. An ET of 78° represents the threshold of sweating, 80° the upper permissible limit for heavy physical labor, 85° the upper limit for moderately hard work, and 90° the upper limit for continuous exposure of heat-acclimatized men engaged in light activities. Based on WB, DB and air velocities, nomograms allow ET to be read. Two scales actually developed: (1) Normal - for Ss "normally clothed and slightly active" and (2) Basic - men stripped to the waist, at rest.	Criticized on grounds of: (1) failure to take work rate into account, (2) nonlinearity with physiological responses to heat, (3) overemphasis on DB at upper end of scale, (4) failure to account for the deleterious effect of low air velocities and the beneficial effects of high air velocities under hot, humid conditions, (5) failure to consider the effects of radiant heating.
Corrected ET	1932	Vernon & Warner	Uses a spherical copper globe 6" in diameter, painted black, into which a thermometer is inserted. Globe measures combined effects of radiation and convection under conditions in which air temperature = wall temperature. A series of studies, using such differential wall and room temperatures, confirmed Yaglou's results that ET was in better agreement with physiological changes than either WB or DB taken separately.	Fails to provide an accurate weighting for WB and, hence, effects of high humidity not accounted for.

TABLE 1 (Continued)

Index	Date	Developed by	Description	Comments
EP (Index of physiological effect)	1945	Robinson et al	Heat stress is evaluated from increases of heart rate, skin temperature, rectal temperature and sweat rate (based on measurements taken on 4 subjects working and resting at various laboratory conditions of temperature and humidity). EP is expressed as a ratio of strain in a given environment to maximum strain in the hottest tolerable environment. Contour curves representing lines of equal physiological strain were plotted against WB and DB temperatures for various known metabolic rates.	Critique: (1) must be used in conjunction with ET for reliability, (2) based on limited sample, (3) metabolic rates of Ss must be known in advance, (4) Ss must be dressed in the particular type of hot-weather clothing used in the studies, (5) still ignores radiation, (6) not applicable to non-acclimatized subjects.
CET (corrected effective temperature)	1946	Bedford	Modification of ET in which radiant heat was included as one of the physical variables by substituting the reading of the black globe thermometer for the dry bulb reading in either the basic or the normal scales.	Requires additional instrumentation such as sling psychrometer for WB and DB, and dry Kata thermometer for estimating air velocity (this estimation not accurate).
Craig Index of Strain	1950	Craig	Similar to EP; heart rate changes and changes in rectal temperature and sweat rate combined to give a single value.	Developed using non-acclimatized, sitting, resting Ss. Critique: As EP, Craig tends to ignore the relative contributions of the physical factors which make up "heat."
P4SR (predicted 4-hour sweat rate)	1952	Wyndham et al	Uses only rate of sweating as a criterion of heat stress in environments that are hot enough to cause sweating. Based on British experimental work, empirical nomograms have been developed for predicting the probable amount of sweat in liters that would be secreted over a 4-hour period by fit, acclimatized men. The nomograms incorporate environmental factors, metabolic rate and the amount of clothing worn.	Critique: (1) P4SR predictions are hampered by the great individual differences in sweat rates, (2) the method is "difficult to apply in the field and is primarily a research tool."

TABLE 1 (Continued)

Index	Date	Developed by	Description	Comments
ETR (effective temperature including radiation)	1950	Yaglou	Yaglou felt that Bedford's correction of ET for radiation, using the globe temperature with the observed WB reading, was unsound since it implies that moisture has been subtracted from the air whereas, in fact, the dew point remains unchanged. ETR uses the observed dew point, and the WB temperature corresponding to the observed globe temperature is found by reference to a psychrometric chart. This WB temperature is now used with the GT to find ET in the usual manner.	Presents the best integration of the physical factors contributing to heat, but still requires measurement of air velocity--a difficult and usually inaccurate procedure.
HSI (heat stress index)	1955	Belding & Hatch	Expresses the heat load in terms of the amount of sweat which must be evaporated in order to maintain heat balance at an arbitrarily assumed skin temperature of 95°F. The evaporation rate required is estimated from the metabolic rate and body heat loss by radiation and convection, using empirical equations or nomographs.	Critique: (1) several of the factors incorporated in this index are currently under study and may need modification (e.g., convection factor and evaporation rates), (2) listed as primarily a research tool, (3) assumption of skin temperature of 95° remains to be justified.
WBGT (wet-bulb/ globe temp. index)	1956	Yaglou et al	Introduced as a simplified substitute for the ETR, designed for use in hot environments, and requires no direct measurement of air velocity. This index may be derived in three ways: 1) WBGT = .7 natural WB + .3 covered GT 2) WBGT = .7 WB + .2 black GT + 1 DB 3) WBGT = .7 psychrometric WB + .3 black GT Variations in the formuli correspond to differing clothing configurations for Ss and different solar-radiation levels for various types of glove	Integrates heat gained from radiation and heat lost through convection, thus combines radiant heat, air movement, air temperature, and humidity into a single value. Critique: WBGT fails to detect wind effects (air movement) in the absence of a radiant heat load; i.e., when mean radiant temperature equals air temperature, the GT will fail to reflect cooling effects due to wind. This

TABLE 1 (Continued)

Index	Date	Developed by	Description	Comments
			thermometers. The WBGT index...is intended for use in outdoor environments where conditions of severe heat stress are attained rarely, if ever, in the absence of solar or long-wave radiant-heat loads (Minard, 1964, p. 12).	restriction is not crucial to heat-stress research since, as Minard (1964) points out: "In the absence of radiant heat, wind effects are relatively less important because heat stress level is low (p. 12).

TABLE 2

Correlation Between Heat-Stress Indices and Evaporative Sweat Loss

Index	Correlation Coefficient with Evaporative Sweat Loss
ETR	.7899
CET	.7839
WBGT	.7798
Globe Temperature	.7232
ET (normal scale)	.6943
Dry Bulb Temperature	.5595
Wet Bulb Temperature	.4606

b. Field tests of the WBGT index have proven it to be highly reliable in predicting decrements in physical performance. In 1954, Yaglou & Minard conducted tests on Marine trainees and found the index correlated well with a number of physiological measures taken during the training exercises. Subsequent summer studies at test stations in Arizona (dry heat) and Florida (humid heat) confirmed these findings. Additional trials in 1955 at the Marine Corps recruit training Depot (Parris Island, South Carolina) resulted in the adoption of the WBGT index in 1956 by the Training Command at that installation; it replaced an index then in use which was derived from air temperature and humidity alone. Under the new program, vigorous training of new recruits (first three weeks of training) was suspended at WBGT readings of 85° or higher; at WBGT 88° or above, vigorous training exercises were suspended for all recruits. Despite hotter weather in 1956, the incidence of heat casualties dropped to 1/3 of the 1955 figure. In 1957 the NAS-NRC subcommittee on thermal factors in the environment included the use of WBGT levels in controlling physical activity and preventing heat casualties at British Air Force and Naval training centers. In 1960 the Marine Corps ordered the use of the WBGT index at all bases where unacclimatized trainees undergo physical training during hot weather. Finally, at a conference held in October 1966, members representing USANLABS, USAERDL, and USAHEL agreed to adopt the WBGT index to specify permissible levels of heat in Army helicopter crew stations.

c. Instrumentation for obtaining WBGT is relatively inexpensive and quite reliable. The British Army is currently developing and testing a prototype WBGT meter which will allow direct readout of the single index value (Peters, 1967).

d. WBGT correlates highly with two other indices currently in use, the CET (.9983) and the ETR (.9768), and will thus provide some basis for comparing results from the present study with those reported by other investigators.

Having selected an index, there remains the problem of specifying the values of that index to be used in the experimental situation. In applied research, index values can generally be chosen on the basis of those which (1) are reported in the literature as correlated with and relevant to the type of performance under study, (2) are capable of being duplicated and controlled accurately in the laboratory, (3) permit subjects to perform for the required times (do not exceed physiological tolerance times), and (4) sample a range broad enough to allow some generalization to operational situations likely to be encountered in the "real world." In addition to these four, a fifth criterion is necessary when selecting WBGT levels, due to the structure of the index itself. The computational formula, WBGT = .7 WB + .2 GT + .1 DB, indicates that (1) as long as the weighted sum remains constant, any or all of the component WB, DB and GT values can change without changing the WBGT index number itself, and (2) any change in the sum, however slight, will result in a new WBGT number. Thus, criterion 5 states that when selecting WBGT levels for heat-stress research, the investigator must not only know the relationship of the index value to the performance being studied, he must also justify his selection of the particular combination of WB, DB and GT used to generate that value. Prospective WBGT values, for example, of 85^{o}, 88^{o}, 90^{o} and 101^{o} could be chosen on the basis of the five selection criteria as follows:

1. Laboratory and field studies have reported decrements in both physical and psychological performance associated with temperatures in this range.

2. WBGT values of 85^{o} and 88^{o} have already been widely adopted as upper thermal limits for moderate and heavy physical activity as well as for specifying permissible crew-station heat loads in Army helicopters. The studies which provide evidence for adopting such values are not directly applicable to pilot performance, but they do suggest that 85^{o} and 88^{o} are productive starting points.

3. These WBGT values can be accurately administered and controlled within most environmental test chambers available.

4. Previous research indicates that no problems will be met at 85^{o} and 88^{o} with Ss engaged in a two-hour performance regimen involving little or no physical labor. It is not known at present whether the 90^{o} and 101^{o} conditions can be tolerated physiologically for this period of time. These extreme values are included (a) to bracket the upper limits for unimpaired mental and psychomotor performance, and (b) because these temperatures have actually been recorded in helicopter cockpits under summer flight conditions (Moreland & Barnes, 1969).

5. Some data is available for choosing values of WB, DB and globe temperatures for each of the WBGT levels. Table 4 lists these values and the source from which they were obtained.

It can be seen from the example that a rigorous and comprehensive selection of WBGT levels is somewhat difficult at present. The difficulties are due, in part, to the fact that worldwide climatic data is available for only two of the three WBGT components; viz., dry and wet bulb temperatures. This data is presented as probability curves for the joint occurrence of the highest wet and dry bulb readings, in the hottest areas of the world, during the hottest months of the year. What is needed to establish true index values for the WBGT scale is an expanded set of three-variable curves representing the highest values of solar radiation which occur in conjunction with existing wet and dry bulb values. Fortunately, worldwide solar-radiation data is currently being collected and, when available, should measurably increase the validity of the WBGT index. Given comprehensive solar-radiation measures, it should be possible to accurately estimate (at least 90 or 95 percent confidence level) the highest ambient WBGT values for prospective

pilot/aircraft operating environments. Once the reliability of such estimates is established, it will, of course, be necessary to determine the correlation between outside and inside crew-station thermal enviroments. These correlations will, in turn, permit the specification of more realistic design parameters for crew-station thermal environments.

TABLE 3

Component Values for Selected WBGT Levels

WBGT No.	Component Values (°F) WB	GT	DB	Source
85°	87.00	73.00	95.00	Each set of figures represents a point on a psychrometric chart (USAERDL, 1956).
	69.00	123.50	120.00	The straight line connecting these points is the "Outside Design Curve" adopted by the Army committee on aircraft crew-station thermal environments (USAHEL Memo, 14 Dec 66). The curve is based on a review of high temperature extremes in AR 705-15 and MIL-STD-210A, with modifications suggested by the Joint Army-Navy-Air Force Manual (TM-5-785) and USAF Climatic Center curves. In essence, the curve represents the probabilities associated with the joint occurrence of WB and DB temperatures during the hottest months, for the hottest areas, worldwide (McDonald, 1964). As such, it includes the highest values recorded in Viet Nam (Natick Labs, 1953; Martorana, 1966).
88°	78.60	114.40	100.90	Based on actual flight measurements of U. S. Army aircraft cockpit temperatures (Joy, 1967; Moreland & Barnes, 1969).
90°	88.99	100.14	97.00	
101°	95.10	122.20	106.70	

Exposure Times

In addition to using a variety of experimental temperatures, investigators have also employed exposure times ranging from 17 minutes (Blockley & Lyman, 1951) to 6 1/2 hours (Reilly & Parker, 1967). The selection of exposure times has been dictated by practical rather than theoretical or empirical considerations. Thus, at extremely high temperautes and/or humidities, physiological tolerance and requirements for subject safety are the principal determinants for length of exposure. In more moderate thermal environments, those known to be physiologically tolerable for specific times, exposure time is determined by such factors as the time required to complete the assigned performance task(s). Even these relatively gross criteria have not been applied consistently, however, and the inability to do so stems primarily from the failure of researchers to agree upon just what constitutes an "extreme" or a "moderate" thermal environment. The problem is further complicated by the existence of such variables as degree of subject acclimatization (discussed under subject variables), which affects both physiological tolerance and the ability to perform. In general, conflicting reports on performance decrement are partly attributable to:

a. Treating exposure time as a dependent rather than an independent variable; i.e., allowing thermal conditions to dictate the length of time subjects remain and/or perform in a given situation. When subjects are unable to remain in one or more experimental conditions for the prescribed time, the resulting information on physiological tolerance, however valuable, is gained at the expense of losing performance data. An example of this type of loss occurred in the early work of Viteles & Smith (1946). Using tasks simulating the operations of naval plotting and chart room, they found no adverse performance effects at ETs of 75° and 80°. At ET 85°, performance decreased only slightly although Ss reported feelings of annoyance and marked discomfort. At 94° ET, "Marked irritability, dizziness, visual blackout and nausea became increasingly common (p. 107)"; none of the subjects was able to complete the tasks. Wing (1965) noted that "Physiological tolerance limits for men exposed to high ambient temperatures have been available for nearly two decades. It has long been suspected, however, that human performance deteriorates well before physiological limits have been reached (p. 960)." Experiments in which subjects are unable to complete the task(s) add little in the way of quantitative evidence to support this "suspicion."

2. Using equal exposure (tolerance) times as a basis for equating thermal conditions. Blockley & Lyman (1951), using temperatures of 160°, 200°, and 235°, RH 40 percent, found little effect on Ss' performance until five to six minutes before they reached their physiological tolerance limits. Pepler (1959), in a quasi-replication of the study found that "It was technically impossible to maintain the very high air temperatures and low humidity of Blockley and Lyman. It was decided, therefore, to use a humid climate which would impose a stress equivalent to their 200° F (93° C) condition, as assessed by the subjects' average tolerance times (p. 383)." The resultant "equivalent" condition was 116° DB, 105° WB and 100 ft/min air movement. Pepler found that decrements in performance were much more severe, and occurred earlier in the testing session. The difference in results is not surprising in light of previous discussion of the components of thermal stress. There is at present no empirical data to suggest that either the qualitative or quantitative (subjective or physiological) stress effects of these different thermal conditions can be safely equated.

3. Assuming that equal exposure times allow thermal conditions of "equivalent warmth" to act with equal effect on performance. Wing (1965), plotting performance decrement (at various levels of effective temperature) against exposure times, commented on this problem:

"Secondly, because the curve is plotted in terms of effective temperature, there is the danger of assuming that all the combinations of temperature, humidity and airspeed which yield a given effective temperature also produce the same degree of performance decrement. This is undoubtedly not the case. Eventually performance decrements should be separately determined for a large number of combinations of temperature, humidity and air movement and reported in a tri-dimensional chart. However, such voluminous data are not yet available . . . (p. 963)."

At present, assumptions regarding the equivalent warmth of WBGT index points, for example, must rely on the indirect evidence that (a) WBGT correlates well with ETR, (b) ETR is a modification of the ET scale and (c) the ET scale was derived from subjective reports of "equivalent warmth" for various combinations of WB, DB and air movement.

4. In a prospective study, an exposure time of two hours would be appropriate according to the following considerations:

a. This figure agrees with the average reported flight time for helicopter missions.

b. It is within the range of physiological tolerance for subjects performing complex psychomotor tasks under two of the WBGT levels selected, 85° and 88°. (In the event that the remaining WBGT levels, 90° and 101°, necessitate shortening exposure time to less than the full two hours, continuous monitoring and recording of performance will still allow accurate comparison of all conditions up to the point of termination.)

A final factor involved in selecting heat-stress exposure times is the lack of reliable information regarding the effects of (a) repeated exposures to high temperatures and (b) continuous exposure to mild or moderate thermal environments for periods of several months. Previous studies have controlled for such effects by random assignment of Ss to conditions. This technique is effective as long as the detrimental effects of thermal stress are assumed to be relatively transient and non-additive. Future study should not make this assumption. Instead, the experimental design should specify that in addition to being randomly assigned to a particular series of temperatures, all subjects receive a 24-hour rest period after each performance trial, regardless of whether the trial is designed as "cool" (control), "hot" (WBGT 85°, 88°) or extremely hot (WBGT 90°, 101°).

SUBJECT VARIABLES

A number of studies such as that by Carlson (1961) indicate that the failure to conclusively demonstrate performance decrement under thermal stress is often due to extreme inter-subject variability. Carlson noted that "although each individual's performance was consistent, the range of performance among the nine subjects was too great to permit definitive analysis of the influences (of heat) on vigilance (p. 10)." This variability is the result of diverse physiological and psychological characteristics which each subject brings, in differing amounts, to the experimental situation. Under the assumptions of random sampling, these characteristics, such as age, physical condition, intelligence, etc., are assumed to be equally distributed among experimental and control groups. Frequently, however, this assumption has not been met, and researchers have often been forced to use whatever subjects were at hand. The acquisition of subjects solely on the basis of availability, incidental sampling as Guilford (1957) terms it, has severely limited the generality of many experimental findings. Unfortunately, the conditions which lead to expediency in sampling are not likely to improve in the near future. For this reason, it is vital that the researcher be fully aware of the role played by subject variables in the determination of performance. Given a knowledge of the relevant variables, there is an increased probability that some controls can be applied, perhaps through modifications of the experimental design and procedures, to limit overall variability within groups.

PHYSIOLOGICAL FACTORS

Adaptation to thermal stress involves changes in a number of physiological systems. For convenience, these changes are summarized in Table 4, prepared by Fox (1965). More detailed descriptions are available elsewhere (Gelineo, 1964; Ladell, 1964; Lee, 1964).

TABLE 4

Adaptive Changes

Mechanism	Adaptation
Sweating	a. Increased capacity* b. Quicker onset* c. Better distribution over body surface* d. Reduced salt content*
Cardiovascular	a. Greater skin blood flow* b. Quicker response* c. Blood flow closer to skin surface d. Better distribution over body surface e. Reduction in counter-current blood vessels
Metabolic	a. Lowered Basal Metabolic Rate b. Lowered energy cost for a given task
Respiratory	a. Hyperventilation*
Heat Storage	a. Increased tolerance to higher body temperature b. A lower resting body temperature*
Behavioral	? ? ?

*Indicates adaptations for which there is agreement regarding experimental evidence gathered to date.

It can be seen from Table 4 that considerable emphasis is placed on those systems most affected by autonomic activity in response to thermal stress. Caution is needed, however, in interpreting the significance of changes in these physiological systems since their activity is, in turn, a function of numerous underlying chemical/biological processes. Until more is known regarding such areas as endocrine balance and hypothalamic regulatory action, the use of heart rate, for example, to represent the entire cardiovascular adaptation to heat will prove less than satisfactory for the purposes of prediction. This criticism is not meant to imply adherence to a rigid reductionist approach, but only to suggest that increased knowledge of certain molecular physiological events <u>may</u> lead to better understanding of the molar processes currently employed as evaluative criteria. Since much of the research on endocrine functions under thermal stress is too detailed for inclusion in this paper, the following summary from a recent review article

(Collins & Werner, 1968) is presented in full; this review provides some indication of the scope and complexity of the problems in this area.

"The pattern of endocrine involvement in the physiological adjustments of homeotherms exposed to high-temperature conditions has been examined. Although the evidence available is in some respects insufficient and reliance has also to be placed on indirect methods, a number of recent studies have contributed important information by the direct measurement of blood hormone levels and turnover. Two main aspects emerge as being reasonably well understood. One is the neurohypophysial and adrenocortical control of water and electrolyte balance, which has been analyzed in some detail. The second concerns the level of thermogenesis that is related to the severity of the heat stress and involves hormones of the pituitary-adrenal-thyroid system. Moderate or gradual heating appears to be associated with a reduced output of these hormones and a suppression of thermothyroid activity accompanied by an increase in metabolic activity.

The evidence supporting these patterns of endocrine response may be briefly summarized:

1. Thyroid activity as measured by ^{131}I uptake and release as well as by histological changes is generally found to be lower in a wide variety of experimental animals exposed to moderately warm (27-34 C) conditions. This hormonally controlled depression of metabolism may be of biological significance for survival in hot climates. For example, tropical indigenes appear to possess a lower BMR than residents in temperate climates though the depression of metabolism is probably small. Rapid or severe elevation of body temperature, however, induces an increased oxygen usage such as may be expected from the Van't Hoff effect; a limited number of animal experiments indicate that this is accompanied by an increase in thyroid activity.

2. There is no adequate proof that the supression of calorigenesis during mild heat exposure involves a reduction in adrenal medullary activity as it does in thyroid activity. In fact, in the bovine and horse (with adrenaline-sensitive sweat glands) the adrenal medulla is responsive to heat stimulation. In man (with cholinergically innervated sweat glands) there appears to be no stimulation of the adrenal medulla during moderate heat exposure, although the evidence is very meager.

3. Judged by the urinary excretion of adrenal corticosteroid metabolites, it appears that glucocorticoid secretion remains unchanged or may be reduced in hot environments. However, little reliance can be placed on urinary metabolites as an index of glandular activity. In blood, 17-hydroxycorticosteroids are raised when the body temperature is elevated rapidly enough; this finding is supported by direct and indirect evidence from animal experiments. The effect of prolonged exposure or of acclimation to heat is not clearly established. Most investigations indicate that the plasma glucocorticoid level or urinary excretion of metabolites is lower in hot climates but this may be accounted for by differences in behavior, nutrition, or body size.

4. In man, aldosterone participates in the regulation of renal and sweatgland losses of salt during exposure to heat. Urinary aldosterone levels increase in the heat, especially if large salt losses have been incurred. The mineralocorticoid activity of other adrenocortical hormones under these conditions has not been investigated. The role of mineralocorticoids in other homeotherms exposed to hot conditions has yet to be resolved, since sweat losses of salt are generally small compared with that in man; in ruminants during dehydration sodium is excreted rather than retained. It is likely that the

renin-angiotensin mechanism of aldosterone control is involved when sweat losses of salt are large but no direct evidence of this is at present available. The action of aldosterone on the eccrine sweat glands of man contributes largely to the reestablishment of salt balance after sweating but the time course of response differs from that of the kidney.

5. Exposure to high temperatures is accompanied by a decrease in urine volume, initially as the result of a reduced renal plasma flow. Antidiuretic hormone is secreted in increased amounts in animals and man even when there is positive water loading in the heat. The stimulus for ADH release may be provided by changes in plasma osmotic pressure and extracellular fluid volume. No evidence has been forthcoming to show that ADH exerts any action on the sweat glands.

6. The hypothalamus exerts a central influence on thermoregulatory processes and in the stress response, food and water intake, osmoregulation, growth, and reproduction. The evidence for hypothalamic control and integration of these functions in hot conditions is discussed in relation to their neural and endocrine basis." (pp. 826-827)

Despite a lack of information regarding the specific biochemical activities involved, the magnitude, rate, and direction of change have been established for such physiological measures as heart rate, blood pressure, respiratory rate and volume, body temperature (oral and rectal) and rate of sweating. The relationship between changes in these measures and changes in environmental heat loads depends largely on the particular physiological mechanism examined. Thus, the correlation of thermal index values with evaporative sweat loss is high; with rate of sweating, it is low (Wilkinson et al. (1964) have suggested that the relationship is actually non-linear). Regardless of the size of the correlation coefficients, however, most researchers have continued to select levels of these physiological measures to operationally define thermal stress; in this definitional capacity they have been useful primarily in setting thermal tolerance limits for subject safety.

Of the various physiological criteria available, heart rate and deep body (rectal) temperature have been most frequently used to indicate the onset of syndromes resulting from overexposure to heat (heat cramps, heat exhaustion and heat stroke). Gold (1960) feels that heart rate, measured through peripheral venous pressures, is particularly important "because it has been noted countless times that the cardiovascular system apparently takes the brunt of heat exposure (p. 1175)." Rohles, Nevins & Springer (1967) present evidence that a rise in rectal temperature and pulse rate also provides "...a stable index of thermal stress." Explicit statements of precise upper limits and/or rates of change for these measures do not appear in the literature, but a review indicates tacit agreement with the values shown in Table 5. In the present study these values will be adopted, although recent research suggests that in the case of rectal temperature they may be conservative (Kaufman, 1963; Pugh, Corbett & Johnson, 1967).

The data provided by Rohles et al. (1967), presented in Table 6, furnishes a basis for estimating whether or not the planned experimental temperatures of the present study will lead to Ss exceeding the rectal temperature and pulse limits of Table 5.

On the strength of their correlation with changes in the thermal environment, numerous attempts have been made to relate adaptive physiological changes to concurrent variations in performance. There is little argument among researchers that some kind of relationship exists, but specifying the parameters which control or mediate its effects has proven extremely difficult for a number of reasons:

TABLE 5

Physiological Limits for Subject Safety in Thermal Stress Research

Physiological Mechanism	Extreme Values	Rate of Change
Heart Rate (Pulse)	140 Beats/min.	15 Beats/min.
Rectal Temperature	102^{o}F	$.2^{o}$/min.

TABLE 6

Mean Pulse Rates and Mean Times for a 2^{o} Rise in Rectal Temperatures

WB(^{o}F)	DB(^{o}F)	Effective Temperature (^{o}F)	Mean Pulse Rates (Beats/minute)	Time for 2^{o} Rise in Rectal Temperature (Minutes)
		Rohles et al. (1967)		
97.2	100	97.2	124.0	81.1
95.5	105	97.0	120.5	67.8
94.5	100	95.2	107.6	99.6
91.9	105	94.4	109.3	138.6
		Present Study		
95.1	106.7	96.8	Ss may be unable to complete 2-hour performance	
89.0	97.0	90.8	Ss should not exceed the limits in Table 5	
87.0	95.0	89.0	Ss should not exceed the limits in Table 5	
69.0	120.0	86.4	Ss should not exceed the limits in Table 5	
78.6	100.9	86.1	Ss should not exceed the limits in Table 5	

1. Effects of physiological change vary with the type of performance being measured. Reliable decrements have most successfully been demonstrated for tasks requiring moderate-to-heavy physical exertion. In this situation, the expenditure of energy in performing places an additional drain on the already overworked physiological systems and thus increasingly augments the effects of the thermal stress already present. The picture is not nearly as clear with respect to effects of heat on complex mental and psychomotor performance since, as Pepler (1960) pointed out:

"Little or nothing is known, however, of the mechanisms or causes underlying these effects. Changes in performance have been observed in the absence of (Watkins, 1956; Weiner & Hutchinson, 1945) or independently of (Mackworth, 1950; Pepler, 1958) changes in the concomitant physiological indices of an effect of warmth, such as body temperature, or the amount of weight lost as sweat (p. 68)."

2. Because changes in physiological measures and changes in performance have each been shown to correlate with exposure to high temperature, it has been assumed that they must also correlate with each other to the same extent. Expirical studies have found this assumption untenable for many complex performance tasks. Bell et al. (1964), for example, reviewed the relation between one physiological response to heat, (body temperature) and visual vigilance. They concluded that:

"No consistent relation, however, has been shown in any of these studies between body temperature or changes in body temperature and changes in performance under adverse environmental conditions, except that a rise in deep body temperature and a deterioration in performance have both been shown to be related to the environmental temperature (p. 287)."

3. Prediction of performance decrement is relatively good at the upper limits of physiological adaptation, i.e., performance decreases rapidly once a subject begins to display symptoms of heat exhaustion or pyrexia. As Hendler (1964) summarized:

"It is obvious that performance and behavior of the individual as an operating entity depends upon the functional status of the parts that comprise the whole. As indicated previously, exposure of the individual to environmental temperature extremes can result in a wide variety of compensatory changes, the overall effects of which can confidently be expected to result in performance decrement when the compensation is insufficient (p. 334)."

Short of this point, however, prediction is poor, and the actual shape of the curve representing performance change as a function of physiological adaptation is unknown.

A final factor which must be considered under physiological adaptation is that of acclimatization. Acclimization is broadly defined as the degree of efficiency of the individual's combined adaptive mechanisms in coping with environmental heat loads. More specifically, the classical picture of acclimatization is described by Fox (1965) as follows:

"The main features are a less marked increase in heart rate while working, lower skin and deep body temperature, a greater production of sweat and, subjectively, a lessened sense of discomfort (p. 66)."

Fox (1964) also reviewed several studies involving "artificial' acclimatization of subjects (artificial referring to acclimatization other than that achieved through actually living and working in a tropic climate). From these studies a picture of the typical laboratory procedure emerges:

"Hot room experiments have usually followed a fairly well-defined pattern. A group of subjects is exposed to carefully controlled climatic conditions for a number of hours daily, during which they perform a known amount of physical work and their physiological responses are measured in terms of heart rate, body temperature, sweat loss and so on. After this initial test, the subjects continue to be exposed to hot conditions for a number of days, at the end of which the first test is repeated. The difference in response between the first and final tests shows the cumulative effect or "adaptation" induced by the intervening heat exposures (p. 66)."

Tables 7 and 8 provide examples of various training regimens for climatic chamber and field acclimatization respectively. In Table 7 (Allan, 1963), the training period was three hours per day for 14 consecutive days under increasingly severe climatic conditions. In Table 8 (TB MED 175) the training time, equivalent in work to marching 2.5 miles per day with a 20-pound pack, is progressively increased and the environmental heat load remains relatively constant.

The following summary presents some important points to be considered in controlling for the effects of acclimatization in heat stress research:

1. Acclimatization represents a process of adaptation characterized by reduced physiological strain under thermal stress. It is operationally defined by specific physiological indices such as sweat rate, heart rate, rectal temperature, etc. As an aggregate of these separate measures, acclimatization is still subject to the limitations described previously for single physiological parameters; it is necessary in establishing physiological tolerance limits, but its utility in predicting performance decrement is best under conditions in which thermal stress approaches those limits.

2. In general, Ss should be acclimatized under the hottest of the experimental conditions planned. There is some evidence that adaptation across climatic conditions occurs, but the exact amount of transfer has not been established. The Army Medical Bulletin mentions this problem and notes:

> "Acclimatization to a hot, dry (desert) environment increases markedly the ability of men to work in hot, moist (jungle) environment; however, for proper acclimization to the latter, residence with regulated physical activity is required (TB MED 175, p. 5)."

It has been noted that the effects of vigorous physical training, even in conditions of cool ambient temperature, serve to increase acclimatization. Allan (1965) compared the effects of training in hot vs. cool conditions and found:

> "Both types of training resulted in a lowering of physiological strain during a standardized heat exposure. The effect was greater for those trained in the hot climate (p. 445)."

Other studies concur regarding the facilitative effects of exercise on acclimatization (Carlson, 1961; Glaser, 1949; Gold, 1961).

3. For studies interested in measuring performance decrement under some standard operational condition involving thermal stress, subjects should be brought to the maximum level of acclimatization possible for two reasons. First, in most field studies or studies simulating operational situations, the interest is primarily in determining the amount of performance degradation which occurs in spite of rather than in the absence of defenses against thermal stress. Thus, in the present study, the focus is on pilot performance

TABLE 7

Example of a Training Programme (Allan et al., 1963)

Time (Minutes)	Activity	Energy Cost ($kcals/m^2$)
0-35	General PT exercises	103.0
36-40	Rest	4.6
41-70	Circuit training (10 tasks)	93.5
71-80	Rest	9.2
81-110	Medicine ball exercises/Relay races	83.0
111-115	Rest	4.6
116-145	Vaulting	88.0
146-155	Rest	9.2
156-180	Minor team games	88.0
	Total for 3 hours	483.1
	Mean energy cost per hour	161.0

TABLE 8

Schedules of Work Acclimatization

	Moderate Conditions		Severe Conditions	
	Desert: (air temperature below 105°F.)		Desert: (air temperature above 105°F.)	
	Jungle: (air temperature below 85°F.)		Jungle: (air temperature above 85°F.)	
	Morning	Afternoon	Morning	Afternoon
First day	1	1	1	1
Second day	1 1/2	1 1/2	1 1/2	1 1/2
Third day	2	2	2	2
Fourth day	3	3	2 1/2	2 1/2
Fifth day	Regular	duty	3	3
Sixth day			Regular	duty

decrement which occurs even with standard ventilation, ad libidum water intake, and a subject who is fully acclimatized. Second, full acclimatization for Ss prior to performance testing avoids the type of confounding reported by Wilkinson et al. (1964) in their study of heat effects on reaction time and auditory vigilance. They reported that "Results...confirm the development of heat acclimatization over the testing periods...(p. 289)." This situation should be avoided until such time as data linking change and/or rate of change of adaptation with performance becomes available.

4. All Ss should be exposed to the full acclimatization training program. A physical examination, however thorough, determines only the "normality" of a S's physiological adaptive systems; it does not insure that these systems will function adequately under extreme thermal loads. Gold (1961) has noted this problem:

> "The philosophy of judging heat tolerance usually takes the form of an "index" that seeks to express physiological 'strain' in terms of numbers. The greater the number, the greater the strain; the lesser the number, the lesser the strain. However, inherent in such a philosophy is the fallacy that the level of strain by itself can constitute an adequate evaluation of heat tolerance. At this laboratory it is felt that two questions must first be answered before heat performance can be properly evaluated. First, to what extent can an individual dissipate heat? Second, how great a price must he pay? Indexes of strain can at best answer only the second question, and, as such, information obtained from them is liable to be quite misleading (p. 144)."

In concluding this discussion of acclimatization, it should be noted that whether taken singly or as a group, the physiological response of any regulatory system, even in a moderate environment, is a function of still other variables which are often overlooked or inadequately controlled. These variables, such as the subject's sex, age, nutritional state, and general physical condition, are discussed briefly in the following section under the heading of "physical" factors.

PHYSICAL FACTORS

Age

Gold (1961) has developed a system for evaluating and selecting heat-stress candidates based on two major concepts: (1) effective body heat storage, Qe, and (2) the index of physiological strain, Ig. Qe is defined as that amount of heat storage obtained if a subject were to enter a heat chamber already equilibrated with it and with all heat-dissipating mechanisms fully operating. Ig expresses accumulative circulatory strain in terms of heart rate alone. From his tests, Gold concluded that "The best subjects (usually in the young age groups) show a low Qe and low Ig; the worst (usually in the older age groups) show a high Qe and low Ig (p. 144)." In another study (Gold, 1960a), he stated that:

> "In young subjects diastolic pressure often drops to very low levels, where as in older subjects there is very little alteration in diastolic pressure and if pulse pressure is increased at all, it is usually accomplished at the expense of a rise in systolic pressure - an undesirable effect in heat." (p. 938)

Gold (1960b) also examined the development of heat pyrexia and noted that older persons are more susceptible because of irreversible circulatory changes; i.e., "...subjects are already compromised in that they are no longer capable of undergoing a full range of compensatory adjustment" (p. 1175). Further evidence for the importance of an age factor in stress research may be found in any listing of "normal" values of physiological functions. A representative listing of norms for three physiological indices is provided in Table 9 (Sunderman & Boerner, 1949). It can be seen that both the amount and rates of change vary as a function of age; it is also evident that age indirectly affects heat tolerance by setting limits for the type and amount of exercise possible in acclimatization training.

TABLE 9

Relationship of Age, Pulse and Respiratory Rates to Body Temperature

	Temperature (Degrees F.)	Pulse Rate (Per Minute)	Respiratory Rate (Per Minute)
Birth - 2 years	98	122	30
	102	141	43
	105	149	50
2-5 years	98	114	26
	102	135	35
	105	161	44
5-9 years	98	103	25
	102	128	30
	105	136	37
9-12 years	98	89	24
	102	117	29
	105	136	31
Adult	98	76	17
	102	106	27
	105	136	34

This type of table would be of greater use, however, if the "Adult" values were specified at intervals of at least five years and tied to some measure of "physical fitness.' Until such relationships are more clearly established, age will continue to be an important but relatively gross determinant of response to heat stress.

Physique

One of the primary physiological mechanisms for heat dissipation is (except in conditions of extremely high humidity) the evaporation of sweat. Evaporative sweat loss is a function of air movement, humidity, amount of sweat produced and the surface area over which the sweat is distributed. The surface area of the skin is in turn determined by the subject's height and weight. Thus, matching on these parameters would aid to some extent in decreasing the variability between subjects with respect to their capacity for body-heat storage as well as the efficiency with which they adapt to thermal stress. The significance of a subject's height and weight are generally overlooked, but their importance is evident in the following description by Gold (1960a) on the calculation of body-heat storage by partitional calorimetry:

> "Figures for the increase in average skin temperature and in rectal temperature...are weighted two-thirds rectal/one-third skin, to yield an overall increase in average body temperature. This latter figure, multiplied by the specific heat of the body (0.83) and kilogram body weight, yields the number of Calories absorbed. Body surface area in square meters is obtained from standard weight-height nomograms. Dividing caloric uptake by surface area, yields Calories per meter square body surface; dividing this figure by time, yields Calories per meter square body surface per hour (Qs)." (p. 934)

In this same article Gold also reported that "Overweight subjects frequently respond poorly to thermal stress (p. 939). This view is supported by the Army Medical Bulletin (TB-MED-175) which states: "The risk of heat injury is very much higher in overweight persons than in those of normal weight, and special care should be exercised when such persons are exposed to high temperatures" (p. 6). Why this occurs is not known, but the most frequent explanation is: The cardiovascular system, a prime factor in body cooling, is already working harder in obese subjects than in normal ones, and the additional amount of strain produced by exposure to heat leads to rapid cardiac overload.

Sex

Although to date none of the studies on heat and complex performance have used female subjects, it should be noted that there are definite sex differences in physiological reactions to thermal stress. In general men exhibit higher sweat rates, a greater decrease in systolic blood pressure, and greater heat production (Morimoto et al., 1967); women demonstrate smaller increments in both rectal temperature and pulse rate (Weinman et al., 1967).

Nutritional State

A subject's state of health, metabolic rate and activity level are factors which interact to determine nutritional requirements and utilization. Unfortunately, while there are numerous graphs indicating caloric requirements for various activity levels, these graphs are seldom keyed to the environmental temperatures. One of the few studies available did examine caloric intake and energy expenditure under desert conditions, but the tasks involved demanded physical labor only (Welch, 1956). Information regarding the type and amount of food best tolerated under conditions of thermal stress is currently unavailable. The Army Medical Bulletin (TB-MED-175, 1957) does suggest that in heat stress situations meals should be cool rather than hot, with the heaviest meal served in the evening. This advice pertains primarily to field conditions, however, and little data is available on how to handle the problem in laboratory studies where conditions are more extreme but exposure times are shorter. In contrast to food requirements, there is a great deal of reliable information available on the amount of salt and water necessary under conditions of high ambient temperature (Army Quartermaster, 1948; TB-MED-175, 1957; Wilber, 1957). Trumbull (1965) has reviewed this literature and suggests that "Today, there appears to be every reason for scheduling food and liquid intake as rigidly as one does the various tasks in an operation" (p. 32). Since individuals differ widely in their metabolic rates, such rigid scheduling may not be possible initially in laboratory studies. If basal metabolism is measured, however, it may prove feasible to equate subjects on this dimension and thus reduce the need for stringent regulation of caloric intake per se. In any case, the important point is that whether the ingestion of solids and fluids is on a controlled or ad libidum basis, the intake should be recorded as accurately as possible for each subject throughout his participation in the experiment. Such comprehensive recording and/or control may be difficult, and will often depend in part on the rapport established between the experimenter and the subjects (this problem is discussed further in the following section on psychological factors). Failure to control or make allowance for subjects' extra-experimental intake can result in the loss of important data, as in the case of Chiles' 1958 study of the effects of high temperature on the performance of a complex mental task. In the hottest (and most interesting) condition, 120°DB/105°WB, Chiles reported that, "Two (of the five) subjects who stated that they were unable to complete the runs had included a fair quantity of alcoholic beverages in their diets the previous evening" (p. 4).

Diurnal Cycle

Basically, the term diurnal cycle (or circadian rhythm, as it is sometimes called) refers to the fact that:

> "Daily fluctuations in physiological function shown maxima and minima which occur regularly at certain well-defined times of day; when several such trends are demonstrable in the same organism, they tend to become entrained under normal conditions of light day/dark night so that their maxima and minima bear a fixed temporal relationship to each other." (Loban, 1965, p. 219)

It is not yet known precisely how these biological rhythms are initiated or maintained, nor are their general characteristics fully understood. This lack of information is due in part to the relatively unpredictable interactions between physiological and psychological factors. As Loban (1965) notes:

"Man is a complex experimental animal, in that his psychological make-up and his proven adaptability tend to insulate him from his natural environment, and it is often difficult to be sure that one is dealing with true circadian rhythms in his physiological processes rather than the mere manifestations of his activity pattern and emotional responses." (p. 219)

Despite the difficulties involved, some progress has been made. The development of daily, repetitive physiological rhythms in infants has been demonstrated (Englemann & Kleitman, 1958). Such rhythms have also been found to occur in adult human subjects, even in the absence of daily environmental fluctuations (Ashoff & Wever, 1962). More recently, there has been a growing interest in the antecedent conditions and subsequent responses associated with the disruption of these normal human rhythms, a condition termed "dissociation." In general:

"Dissociation between human physiological daily trends is best demonstrated in those functions which normally display clearly-marked maxima and minima and are little affected by minor emotional changes. The most satisfactory rhythms for experimental purposes have been found to be those of body temperature and of renal excretion...The dissociations to be described have been studied under two main sets of conditions: 1) when the outside environment remains relatively constant throughout the 24 hours of the day and subjects are asked to live on abnormal time routines, and 2) when the normal 24-hour periodicity is maintained in the subjects' activity patterns but changes are present either in the environment or in the capacity of the subject to respond to the daily environmental fluctuations." (Loban, 1965, p. 220)

A study by Simpson & Loban (1967) exemplifies research conducted under condition 1 (abnormal routines). Using adult male subjects, they examined the effects of a 21-hour day on excretory rhythms of 17-hydroxycorticosteroids (17-OHCS) and electrolytes (sodium, potassium and water). Their results indicated that:

"...adaptation of the 17-OHCS and potassium rhythms took at least five weeks while that for sodium, chloride and water tended to be more rapid but was not immediate. These differences in the response of the various rhythms resulted in a loss of their normal synchronisation (i.e., maxima about midday, minima at night). A particularly interesting finding was that when experimental "days" fell on periods corresponding to deep sleep periods at home, adaptation was very slow. 24-hour controls taken at the end of the 21-hour day experiment were normal. This indicates the fundamental nature of the 24-hour period in the promotion of these excretory rhythms." (p. 1205)

This demonstration of altered 17-OHCS as a function of change in routine is particularly important because of the growing use of 17-OHCS as an index of "stress" (Hale & Shannon, 1967). Aircraft crew members, for example, depending upon performance requirements, are frequently exposed to abnormal routines and/or unusual environments, and these conditions themselves may have provided much of the "stress" that has been measured in experiments using 17-OHCS as an index.

In addition to changes in biochemical excretions, circadian variability is beginning to be associated with changes in human performance in such areas as visual and auditory vigilance. Frazier, Rummel, & Lipscomb (1968) tested subjects on systems monitoring, visual reaction time, communications and visual stimulus matching over a 14-day period of confinement (not isolation). They reported that:

"...Circadian rhythmicity was identified in every measure employed, but individual circadian periods showed clear nonstationarity as time progressed, with periods ranging considerably above and below 24 hours. This finding raises some questions regarding the common practice of using time-of-day control for eliminating circadian periodicity as a source of error variability and questions regarding whether circadian variation might account for vigilance performance changes previously associated with length of a monitoring vigil. The results also suggested that confinement stress can lead to alterations of circadian rhythmicity, even when the physical environment and activity schedule are held highly constant." (p. 383)

In another study, Colquhoun (1960) found that the efficiency with which subjects detected brief, rarely appearing signals in an inspection task was a joint function the time of day the tests were given and the subjects' personality.

Studies such as this, as well as the type of experimental approach initiated by Iberall and Cordon (1965) suggest that physiological systems may show intra-system variability of a more complex nature than previously suspected and point strongly to the need for experimental control of diurnal influences on performance. Briefly, some implications of circadian variability for thermal-stress research are:

1. Ss' extra-experimental living routine should be monitored to insure that occupational or social adaptations have not restructured their "days" and "nights."

2. Where change in physiological function is used as an index of stress, "baseline" measures of "normal" activity levels should be obtained for those periods of the day during which Ss will be exposed to experimental conditions.

3. Whenever possible, exposure of Ss to experimental and/or control sessions should be equally distributed with respect to time of day (or night) during which performance is measured; e.g., at least allow for a two-way classification such as:

	AM	PM
Experimental group	Performance Scores	"
Control group	"	"

4. If (3) above is impractical, then care should be taken when interpreting differences between an "early-morning" control ground, for example, and a "mid-afternoon" experimental group. This is particularly important in a repeated measures design; i.e., when all Ss undergo all treatment conditions.

General Health

There is little disagreement over the thesis that, regardless of the environmental conditions, the quality and quantity of an individual's performance is greatly influenced by his general state of health. Surprisingly little information is available, however, on the exact effects of the various clinical syndromes on specific types of performance. In the case of performance under thermal stress, this lack of data compels the investigator to select experimental subjects who are demonstrably symptom-free. This selection criteria is particularly important, since one of the most generalized body responses to disease is the production of a febrile state. Behavioral

manifestations of high core temperatures associated with disease entities appear to be quite different than those observed in conjunction with exertion under conditions of high ambient temperature; e.g., marathon runners often sustain body temperatures in excess of 103^{o}F without noticable mental aberrations, while individuals with the same body temperatures due to disease have been known to suffer delusions, hallucinations, and even loss of consciousness.

In addition to its direct chemical-physiological impact on mechanisms involved in adaptation to thermal stress, disease can also affect an individual's performance via his response to his symptoms; i.e., such psychological factors as motivation may be affected by the subject's conception of the type of tasks and achievement levels expected of "sick people.' Thus, one subject might perform poorly even if his illness were relatively minor, while another with a similar degree of pathology might attempt to "overcome" the limitations of his symptoms. In either case the result is a magnification of variability in performance in an area where both intra- and inter-individual differences are already large because of the effects of numerous other uncontrolled or poorly controlled subject variables.

Physical Condition

In a preceding discussion of the role of physiological adaptation systems in the process of acclimatization, it was noted that a physical examination of potential subjects generally provides information only about the condition of the body at the time of the exam (which is administered under non-stressful environmental conditions). With respect to the manner in which the body will respond to heat, the exam provides, at best, a probability statement; i.e., it does not insure that the physiological systems involved will function adequately under extreme thermal loads. In a similar manner, many of the routine tests of "physical fitness" currently employed fail to provide the researcher with an accurate appraisal of such relevant factors as: a subject's muscle tonus, the amount and rate of muscular activity of which he is capable, his respiratory and cardiovascular recovery rates, the efficiency of his oxygen uptake and utilization, etc. Balke and Ware (1959), for example, evaluated the work capacity of 500 military and civilian Air Force personnel. Measuring the cardiovascular response, oxygen consumption and pulmonary ventilation of subjects performing on an ergometric bicycle, these investigators concluded that, according to an arbitrary rating scale of work capacity, 42 percent of the test population were in "poor" condition, 40 percent "fair", and only 18 percent in "good" or better physical condition. To minimize the problems generated in this type of situation, subjects in future environmental stress studies should be subjected to stringent examinations:

1. Capable of evaluating dynamic physical performance as well as static organ condition.

2. Given under at least one of the environmental stress conditions to which the potential subject will be exposed, preferably the most extreme.

3. Administered often enough throughout the study to detect or prevent the onset of pathology and quantify the rate of acclimatization for both aggregate and individual physiological systems.

PSYCHOLOGICAL FACTORS

It is beyond the scope or intent of this paper to evaluate or categorize the multitude of psychological variables which undoubtedly play some part in the individual's response to environmental stress. Instead, the following sections will be limited to relatively brief discussions of broad concept areas such as fatigue, skills and abilities, personality and motivation. Within each of these areas there are, of course, many problems of measurement, validity, reliability and, above all, definition. As Mandler and Kessen (1964) have noted in their examination of the language of Psychology:

> "Definitions play a ubiquitous role in any developing field of knowledge; they are given the major burden of introducing new terms and of purifying the old ones. It may well be the mark of maturity for a science that it can dispense with intricate questions of definition because its terms are invariant in response to events and within laws and theoretical sentences. Until that great time arrives, psychology must concern itself with definitions, redefinitions, and other linguistic crutches." (p. 103)

With the increased reliance upon operational definitions, there has been a corresponding proliferation of concepts, each circumscribed by the particular set of operations involved in its measurement. Thus, depending upon the number and type of studies examined, there are many definitions of "motivation" or "personality" available as well as a number of projective and objective tests for measuring their impact on performance. Although each of the following discussions is limited to the examination of one or two approaches to a given concept, it should be understood that these approaches do not represent a preferred definition nor do they constitute ann endorsement of any specific methodology or quantitative testing procedure. The researcher must himself assess the degree of "surplus meaning" associated with a given concept, derive his own definition, and develop a measurement technique appropriate to the particular experimental conditions to be used. The intent here is to emphasize that in the future studies of thermal stress the attempt must be made to measure the effects of certain psychological variables upon performance. If measurement techniques appear to be inadequately developed or unreliable, then these variables should be controlled through the use of rigorous sampling, experimental design, and statistical analysis. Though the "state of the art" in measurement may leave much to be desired, psychological variables cannot be ignored.

Fatigue

In his presentation of the Ergonomics Society Lecture, Grandjean (1968) provides an overview of some of the problems associated with determining the physiological and psychological significance of fatigue. As expected, the first problem is that of definition. Grandjean notes that:

> Physiologists very often consider fatigue simply as a decrease in physical performance. Psychologists try to consider it as a condition affecting the whole organism, including factors such as subjective feelings of fatigue, motivation, and, of course, the resulting deterioration of mental and physical activities. The term "fatigue" is thus often used with different meanings and is applied in such a diversity of contexts that it has led to a confusion of ideas. (p. 427)

Grandjean himself favors a neurophysiological definition in which the recticular activating system (RAS) interacts with various limbic (emotional) and cognitive activities of the individual to produce the symptoms of fatigue. More specifically, he defines fatigue as a retardation of cortical activity resulting from either (1) increased inhibition of the ascending RAS-"active" inhibitory function, or (2) lowered sensory input or diminished corticofugal feedback-"passive" inhibitory function.

With respect to the symptoms of fatigue, Grandjean states:

> The symptoms of fatigue are clearly seen and clearly felt:
>
> decrease of attention
> slowed and impaired perception;
> impairment of thinking
> decrease of motivation;
> decrease of performance for phvsical and mental activities. (p. 431)

According to a review by Trumbull (1965) however, there are many instances wherein these symptoms, regardless of how clearly seen and felt, are not reflected as decrements in subjects' subsequent performance. In fact, subjective reports of fatigue often fail to correlate with lowered efficiency during task performance.

Grandjean explains these discrepancies on the basis of external stimuli and heightened RAS activity:

> It is most probable that the same alerting mechanism may occur in many test situations when we try to measure fatigue: a task which is new and requires a high performance will produce in the subject a stimulation of the activating system and will therefore mask a previous state of fatigue-at least for a certain time and to a certain extent. This mechanism is one of the reasons why many fatigue tests give disappointing results. (p. 429)

He goes on to present what he considers a productive approach to developing reliable and valid tests for fatigue. His method is essentially that of correlating self-rating test scores (from adjective check lists) with various psychomotor and physiological responses (e.g., critical fusion frequencies, grid tapping, etc.). The actual correlations reported are, however, disappointingly low despite their statistical significance.

For example, the Pearson r for grid tapping and scores on the "refreshed-tired" continuum is .32 which, when squared, accounts for about nine percent of the variance for these test scores. Other correlations of a similar nature tend to support Grandjean's own evaluation of the current status of efforts in fatigue measurement:

In ergonomics, we would appreciate a method which would allow quantitative measure of fatigue with comparable results for different working situations. Physiologists and psychologists have tried hard to develop such a method, but the results have been disappointing until now. (p. 431)

In summary it appears that in spite of a great deal of research the problem of meaningful quantification of the symptoms of fatigue remains. Actually, the methods available for achieving this goal do not appear to differ greatly from those proposed by Bills in 1943. He suggested that there were four kinds of fatigue which could be recognized and measured by four corresponding techniques as shown in Table 10.

TABLE 10

Components of Mental Fatigue

Measurement Method	Fatigue Symptoms	Task Associated Measures
Objective	Diminished capacity for work	Decrement in output (productivity)
Organic	Decrease in energy	Lowered metabolic rate
By-product	Decreased muscle tonus Reduced emotional control Increased body movement	Amount of lost motion Release of uselessly distributed tension
Subjective	"Feelings" of tiredness	Pre-post self-ratings (adjective checklists) Questionnaire responses

In thermal stress research, the problem of fatigue may be attacked by any or all of the methods in Table 10. An alternative approach, however, is to treat fatigue as an intervening variable and control for its physiological effects on performance by merely allowing subjects suitably long rest periods in which to recuperate from the effects of exposure to "hot" test conditions. The psychological effects of fatigue, depending upon the type of task used, can be controlled for through the use of randomized group designs and/or the use of pretest performance scores for matching subjects. Once performance degradation has been reliably associated with known thermal environments, then the causal or mediating effects of variables such as fatigue can be further investigated.

Skills and Abilities

In the previous sections on the selection of subjects for thermal-stress research, variables such as metabolic rate, physiological functioning, and physical characteristics have been treated, for simplicity, as though they were independent. This, of course, is not the case at all. These systems do interact with the individual's perceptual and cognitive activities in an extremely complex manner, and the significance of these interactions is nowhere more apparent than in the area of human skills and abilities. Fleishman and his coworkers have spent a number of years investigating the growth and development of human abilities as they relate to the acquisition of various psychomotor skills. The remainder of this section is based on a synopsis of this work (Fleishman, 1966, 1964; Gagne & Fleishman, 1959). Divergent viewpoints on this subject can be found in review articles and collections such as that edited by Bilodeau (1966).

Fleishman begins by defining ability:

> As we use the term, ability refers to a more general trait of the individual which has been inferred from certain response consistencies (e.g., correlations) on certain kinds of tasks. These are fairly enduring traits, which in the adult, are more difficult to change (Fleishman, 1966, p. 147)

Despite their enduring nature, however, Fleishman does not imply immutability in these traits, and readily acknowledges the role of interaction by stating:

> Many of these abilities are, of course, themselves a product of learning, and develop at different rates, mainly during childhood and adolescence. Some abilities (e.g., color vision) depend more on genetic than learning factors, but most abilities depend on both to some degree (p. 148).

Defining skill as the level of proficiency on a specific task or group of tasks, Fleishman next relates the learning of skills to the abilities possessed by an individual according to the following propositions:

1. Some abilities may transfer to the learning of a greater variety of specific tasks than others e.g., verbal abilities (Fleishman feels that the concept of intelligence really refers to a combination of primarily verbal skills which contribute to achievement over a wide range of activities).

2. Although human adults show marked learning over time in almost any type of specific skill, the rate of learning and the final level achieved are both limited by the degree to which certain underlying, basic abilities have been developed through the interaction of genetic and environmental interactions.

3. The relative stability of basic abilities allows useful predictions to be made regarding an individual's subsequent performance (skill level) on more complex, specific tasks.

If the above propositions are assumed valid, then the next step is to develop a taxonomy or systematic classification of human abilities. Fleishman has done this in the areas of perceptual-motor and "physical fitness" performance through the use of factor analytic techniques. Table 11 lists the "basic" psychomotor abilities he has identified to date (Fleishman, 1966).

TABLE 11

Taxonomy of Basic Psychomotor Abilities

Ability	Definition
Control Precision	Factor common to tasks which require fine, highly controlled, but not overcontrolled, muscular adjustments, primarily where larger muscle groups are involved
Multilimb Coordination	The ability to coordinate movements of a number of limbs simultaneously
Response Orientation	A factor found general to visual discrimination reaction psychomotor tasks involving rapid directional discrimination and orientation to movement patterns. It appears to involve the ability to select the correct movement in relation to the correct stimulus, especially under high-speed conditions
Reaction Time	The speed with which the individual is able to respond to a stimulus when it appears. There are some indications that individual differences in this ability are independent of whether the stimulus is auditory or visual and also independent of the type of response required
Speed of Arm Movement	Speed with which an individual can make a gross, discrete arm movement where accuracy is not a requirement
Rate Control	Involves the making of continuous anticipatory motor adjustments relative to changes in speed and direction of a continuously moving target or object. General to tasks involving compensatory as well as following pursuit, and extends to tasks involving responses to changes in rate
Manual Dexerity	Involves skillful, well-directed arm-hand movements in manipulating fairly large objects under speed conditions
Finger Dexerity	Ability to make skill-controlled manipulations of tiny objects involving, primarily, the fingers
Arm-Hand Steadiness	Ability to make precise arm-hand positioning movements where strength and speed requirements are minimal

This taxonomy is presented as an example of one approach to the problem of individual differences in abilities. In actual practice, the use of such a taxonomy to predict performance on a specific task, regardless of the environmental conditions under which the testing takes place, necessitates gathering the following data:

1. The abilities required by the specific task to be used

2. The relative contribution of each ability over time to overall performance scores.

3. The degree to which each subject possesses each of the "basic" abilities to be drawn upon by the experimental task.

4. The extent to which differential distribution of these abilities across subjects mediates learning and final achievement levels.

If fiscal, temporal, or personnel constraints preclude the systematic collection of this type of data, then the researcher should insure that he has a rationale for the selection of subjects based, at least in part, on some type of standardized qualification test(s). In some instances such a pretest might employ the identical task to be given under the experimental conditions, in others it could involve measurement of some ability which has been shown to correlate highly with performance of the experimental task. If this procedure is followed, then, as Fleishman points out,

> The subjects' pretask abilities become major treatment variables with significant interactions with learning trials and with other learning phenomena (Fleishman, 1966, p. 165).

In addition, a knowledge of pretask abilities and skill levels allows the researcher, through the use of such techniques as multiple regression and covariance analyses, to determine treatment effects which occur regardless of subjects' initial levels of competence or rates of learning, i.e., treatment means can be more accurately adjusted to reveal the magnitude of performance decrements attributable only to changes in experimental conditions.

Personality

In their paper on the relationship between personality traits and psychomotor responses of subjects performing in high ambient temperatures, Blyth and Lovingood (1964) began by observing:

> Many of us have had the experience of watching two or more men of nearly equal physical capacity placed in a trying situation, and then noting that one of them quits the task, while the other perseveres. It is extremely difficult, if not impossible, to explain this difference in performance level solely on a physiological basis. Therefore, the hypothesis that some aspect of the physiological makeup or personality structure may be responsible for this observed variation in performance is certainly worthy of intense and concentrated investigation (p. 241).

Significant relationships (chi-square analyses) between the variables measured by Blyth and Lovingood are shown in Table 12, reproduced in its entirety from their 1964 article (p. 244).

TABLE 12

Significant Relationships Between Experimental Measures
Temperament, and Criterion Measures

	Competitiveness	Actiye	Vigorous	Impulsive	Dominant	Emotionally Stable	Sociable	Reflective
Coordination (two-hand)	+5.368 (.05)							
Heart rate								
Tapping			+5.368 (.05)				+5.368 (.05)	
Rate of addition								
USES peg board II (inversion)								
USES peg board I (transfer)								
Simple reaction time time to light								
Hand and arm steadiness						-3.359 (.05)		
Strength		+3.359 (.05)						

Key: In each row the top entry shows the the value of chi-square, and the bottom entry shows the level of significance. Plus (+) indicates the association is positive between the desirable change on the experimental variable and a high score on the trait. Minus (-) indicates the reverse is true.

The seven traits listed across the top of Table 12 represent personality dimensions as measured by the subjects' scores on the Thurstone Temperament Schedule. In addition to these scores,

> Each subject of this experiment was given a rating as a competitor. This was a composite rating made by three examiners who monitored the performance of each subject. No clear-cut definition was available of what constitutes competitiveness or a strong competitor in this situation. In view of this, the following factors were arbitrarily chosen by the investigator as imoortant criteria for selection of men performing in a stressful situation:
>
> a. Did the subject volunteer for the experiment?
>
> b. Did the subject make frequent complaints?
>
> c. Did the subject seem to exert himself fully when taking the strength tests given inside the heat chamber?
>
> d. Did the subject seem to encounter stress symptoms such as headaches, dizziness, general weakness, unusual thirst, "cottor mouth," etc.?

e. Did the subject take pride in his accomplishments or achievements on the various test items?

f. Did the subject inquire about the performance of others?

g. Did the subject seem to be of even temperament or disposition?

h. Did the subject regard the experiment as a challenge or simply an experience to be tolerated and endured? p. 242)

There are, of course, certain deficiencies present in this type of exploratory study. For example, no data are provided with respect to the validity of the evaluative criteria, nor are intra- or inter-judge reliability coefficients furnished; the results and discussion section consists primarily of the brief statement of results with little or no discussion. Despite these criticisms, however, the study does embody a workable approach to the problem of determining the interaction of "personality" traits with performance under thermal-stress conditions. Thus, the finding that "...the significant negative relationship between hand and arm steadiness and the emotional stability trait is not at all clear" should not detract from the value of having demonstrated that such a relationship does in fact exist.

In the thermal stress literature reviewed, only one other study was found in which a personality trait (emotional stability) was assessed in conjunction with performance of cognitive tasks under high ambient temperature (109°F dry bulb, 40% relative humidity). Using the Ranking Rorschach Test (RRT), Givoni & Rim (1962) attempted to measure the degree of their subjects' neuroticism. In the RRT (Eysenck's modification of the Harrower-Erickson technique),

> The subject sees one Rorschach card at a time; he is also furnished with a list of nine possible answers which might be suggested by the ink-blot. He is required to write a 1 after the response which seems to him most like the ink-blot, a 2 after the response which seems to him secondmost like the ink-blot, and so on down to 9, after the response which seems to him to be least like the ink-blot. There are four neurotic and five normal responses to choose from for each card (p. 103)

Subjects in this study were also administered the Dominoes Test for intelligence which is defined by Buros (1953) as a 'g'-Saturated Test. "G," according to Vernon (1951), depends on the general mental energy with which each individual is endowed--it is innate and relatively unaffected by experience. Finally, subjects were given two subjective response scales to estimate the degree of environmental stress (see Table 13 - Givoni & Rim. 1962, p. 103).

Individual differences, both physiological and psychological, were large, as the authors note:

> There is a remarkable spread of the results. Therefore, no clear relationship exists between performance and environmental stress, either in its physiological or subjective manifestations (p. 109).

The personality measures, per se, also failed to correlate significantly with either physiological or performance scores but Givoni and Rim found what they consider enough trend data to support the following conclusions:

TABLE 13

Subjective Responses Scale

Thermal Sensation	Sensible Perspiration
1. Very Cold	0. Skin Dry
2. Cold	1. Skin Clammy (Feels moist to touch)
3. Cool	2. Skin Damp (Perspiration just visible)
4. Comfortable	3. Skin Wet (Sweat covering the surface, drop formation)
5. Warm	4. Parts of the Clothing Wet
6. Hot	5. Most of the Clothing Wet
7. Very Hot	6. All of the Clothing Saturated

1. The results support the hypothesis that both quality and quantity of performance are a function of intelligence while emotional stability does not affect performance (p. 114).

2. Under these conditions the results suggest that the environmental stress in the range of this study, and for short periods, does not limit the ability to concentrate and perform standard computations. It may be, however, that at more prolonged time people would not be able to maintain their ability at their best (p. 114).

The studies outlined exemplify two approaches to investigating the way in which personality variables mediate subjects' performance under thermal stress. A coherent description of the processes involved, however, will eventually require clarification of certain other relationships. The following points, keyed to Figure 1, constitute a brief summary of the relationships traditionally emphasized in thermal stress research plus those which have received little attention to date.

1. Thermal Stress and Personality (A→B)—Illustrated in the Givoni and Rim study, this relationship is rarely examined but important since there is some evidence that prolonged thermal stress (even when physiologically tolerable) may lead indirectly to performance decrement by producing increased irritability and decreased motivation in the subject.

2. Thermal Stress and Quantitative Performance Measures (A→C)—Investigation of this relationship forms the basic paradigm for the majority of studies examined in the literature review. In this approach little or no attempt is made to assess the possible mediating effects of personality factors on performance.

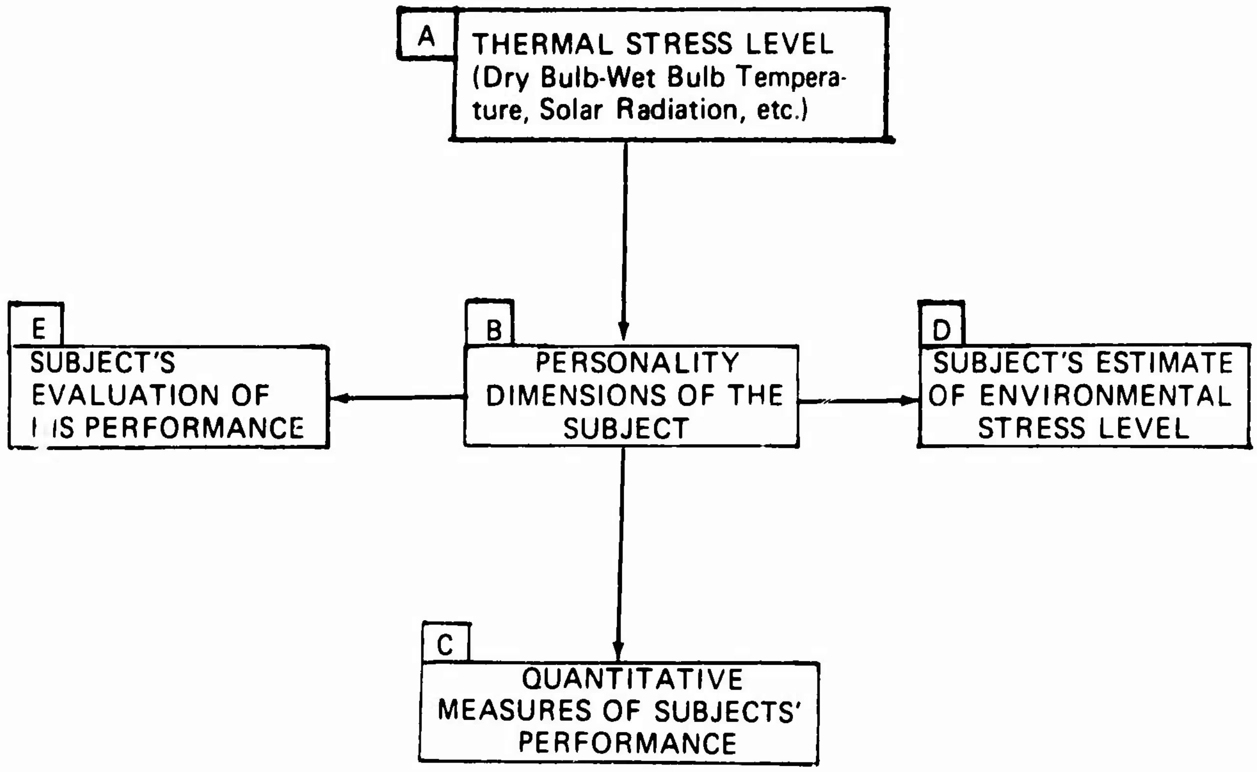

Fig. 1. SCHEMATIC REPRESENTATION OF THE INTERACTION OF PERSONALITY FACTORS WITH THERMAL STRESS LEVELS AND PERFORMANCE MEASURES

3. Thermal Stress and Subject's Estimation of Stress Level ($A \rightarrow D$) —Generally, comparisons of this type involve correlations between:

(a) Ss' rating-scale judgments and instrument measures of the thermal environment.

(b) Ss' rating-scale judgments and their physiological responses.

(c) Ss' numerical estimates and recorded thermal values.

Because of the differences in the precision of measurement of Ss' responses in the above approaches, it is not surprising that results are often conflicting. For example, Fine (1958) using (b) found "...a high degree of agreement between the subjective-rating method and both mean weighted skin temperature and metabolic-rate methods of ranking the environmental conditions (p. 355)". In contrast, Mooreland and Barnes (1969) using (a) found that helicopter pilots flying under high ambient cockpit temperatures were poor judges of the actual ambient temperature levels. It is probable that conflicting results are also a function of failure to consider the influence of training and experience on the ability to judge environmental conditions. The role of training should be further studied since the judgments of trained "experts" constitute the basis of a number of stress indices such as the effective temperature scale.

4. Thermal Stress and Subject's Evaluation of Own Performance ($A \rightarrow E$).—No data is available regarding the strength of this relationship. It seems reasonable to assume that a correlation does exist, probably negative, but that effects of the thermal environment do not affect the subject's estimate of his performance directly. Rather, thermal-stress effects are mediated by personality variables (Block B) and are expressed as changes in $B \rightarrow D$ and $B \rightarrow E$ discussed in points 6 and 7 below.

5. Personality and Quantitative Performance Measures ($B \rightarrow C$)—This type of relationship is a common research topic in social and clinical psychology, but the effects of physical environmental stressors such as heat are seldom considered (the Blyth and Lovingood study is an exception). Even in studies ostensibly concerned with other aspects of stress, however, the effects of $B \rightarrow C$ occasionally intrude in a manner impossible to ignore. Teichner, for example, in his study of the effects of external reinforcement on length of voluntary exposure times, found it necessary to tell his subjects, "You will not be proving masculinity by remaining in the cold. There is no relation between manliness and tolerance of the cold" (Teichner, 1967, p. 505). Here is a case where internal, personality related, reinforcement was potentially strong enough to confound responses to external rewards (money).

6. Personality and Subject's Estimation of Stress Level ($B \rightarrow D$)–Not a great deal is known about this relationship, but it merits investigation for at least two reasons. First, it is tacitly acknowledged that an individual's self-concept is strongly influenced and directed by membership in a particular group or groups; group values become basic determinants of a variety of the individual's responses, including his reactions to stressors. This situation is particularly noticable in military organizations and has considerable import for any program attempting to formulate crew-station design standards based solely on crew members subjective evaluation of stressor levels. It is difficult, for example, to get pilots to make formal "complaints" or derogatory evaluations of cockpit operating temperatures. Informally, where the need to live up to the role of being able to cope with any adversity is less, complaints can be and are made. A related problem here is that of volunteer subjects. Regardless of monetary incentives, it has been argued that volunteers, particularly those for experiments listed as requiring "hazardous duty," are a select group whose behavior is motivated by a need to excel and to demonstrate that they can "take it." A second situation, one almost directly opposite that found with pilots and volunteers, can be found

to stem from the B→ D relationship. Frequently, it is found that some percentage of subjects derive little or no satisfaction of internal needs from participating in an experimental task. A high level of performance is of no interest to them, i.e., aspiration level, need to achieve, need for closure, etc., are low or nonexistent. In this case, it is possible that in response to other needs at B, spuriously high estimates at D may be given with the aim of terminating the test and removing the subject from the situation.

7. Personality and Subject's Evaluation of Own Performance (B→E)–In the absence of feedback (knowledge of results), where he is unable to rank his performance against some maximum possible score or the scores of others, a subject will still form some opinion of his performance. Regardless of the degree to which this opinion or estimate corresponds to an objective ranking of performance (i.e., Strength C→ E), it may strongly influence the validity of the subject's evaluation of environmental stress. If the subject feels he is performing poorly then he may knowingly or unknowingly through some form of ego defense, overestimate the severity of stress; conversely, if he feels he is performing well he may tend to belittle or underrate the stress conditions. In either case, strength of A→D may actually be a function of B→E, given that an accurate estimate of C→E is impossible for the subject. In a less indirect manner, the subject's evaluation of his performance as poor or unsatisfactory may initiate a feedback cycle resulting in ever-increasing performance decrement. Failure to perform leads to greater and greater anxiety which, in turn, interferes with both learning and performance. This cycle, of course, operates to a certain extent in the opposite direction with mastery of the task and improvement in performance leading to decreased anxiety and selfconsciousness and hence, even better performance over time.

8. Quantitative Performance Measures and Subject's Estimation of Stress Level (C→ D)–Similar to the A→ D) relation discussed in (4) above, i.e., some correlation can be found but the magnitude and sign are probably more dependent upon the intervening effects of factors in Block B.

9. Quantitative Performance Measures and Subject's Evaluation of Own Performance (C→E)–The strength of this relationship has been widely used in psychological research as an indirect assessment of the personality dynamics underlying an individual's behavior. What is needed in future thermal-stress research is a comparison of C→ E under "normal" or "comfort" conditions and conditions of high ambient temperatures and humidities; this is particularly important in light of the discussion of the possible effects of the B→ E relationship (7 above).

10. Subject's Estimate of Stress Level and Subject's Evaluation of Own Performance (D→ E)–An examination of this relationship could, depending upon the sign and value of the correlation, indicate the extent to which one might infer the differential operation of personality traits in the subject population. Thus, if the degree of correspondence between A→ D and C→ E are high, and D→ E near zero, the role of personality factors could be considered as minimal (at least in that particular experimental situation).

In concluding this section on the importance of personality variables in thermal stress research, two important additional factors can only be touched upon here. The first deals with the fact that the subject has been considered as performing, under heat stress, in relative isolation from both the experimenter and other subjects. That this situation seldom obtains is obvious. Trumbull (1965) has summed up the problem in two points:

1. We are just beginning to learn the degree and frequency with which we can change the leadership-group composition, and task variables and still maintain performance. It is a sensitive thing, this performance of a group.

2. A person too concerned about others' observation, perception, or acceptance of his performance is not in a position to make his maximum contribution.

Regarding the subject's relation to the experimenter, Argyris (1968) feels that a rigorous experimental approach can lead to some of the following consequences:

1. Physical withdrawal which results in absenteeism and turnover.

2. Psychological withdrawal while remaining physically in the research situation. Under these conditions the subject is willing to let the researcher manipulate his behavior, usually for a price. The studies that show subjects as all too willing to cooperate are, from this point of view, examples of subject withdrawal from involvement and not, as some researchers suggest, signs of subject' high involvement. To give a researcher what he wants in such a way that the researcher does not realize that the subject is doing this (a skill long ago learned by employees and students) is a sign of nonresponsibility and a lack of commitment to the effectiveness of the research.

3. Overt hostility toward the research. Openly fighting the research rarely occurs, probably because the subjects are "volunteers." If they are not volunteers, they may still feel pressured to participate. If so, they would probably not feel free to fight the researcher openly.

4. Covert hostility is a safer adaptive mechanism. It includes such behavior as knowingly giving incorrect answers, being a difficult subject, second-guessing the research design and trying to circumvent it in some fashion, producing the minimally accepted amount of behavior, coercing others to produce minimally, and disbelief and mistrust of the researcher (Argyrus, 1968, p. 186).

Argyrus also notes that, "...the exact degree to which any of these conditions would hold for a given subject would be, in turn, a function of:

1. The degree to which being independent, manipulated, and controlled is "natural" in the lives of the subjects (e.g., research utilizing children or adults in highly authoritarian cultures may be more generalizable).

2. The length of time that the research takes and the degree of subject control it requires.

3. The motivations of the subjects (e.g., for the sake of science, to pass a course, to learn about self, for money).

4. The potency of the research (the involvement it requires of the subject).

5. The possible effect participation in research or its results could have on the subject's evaluation of his previous, and perception of his future, life.

6. The number of times the subject participates in other research.

7. The degree to which the research situation is similar to other situations in which the subject is immersed, about which he has strong feelings, few of which he can express" (p. 187).

The second factor which has not been treated in depth is the interaction of task and personality variables. Although he does not refer specifically to personality dynamics, Wilkinson (1969) has written an excellent review of the factors in the working situation which mediate the impact of thermal stress on performance. Briefly, these are:

1. Duration of work on the task.

2. Familiarity of the operator with the stress and the work to be done under the stress.

3. Level of incentive of the operator.

4. Kind of work he has to do.

5. The aspect of performance deemed most important.

6. The presence of other stresses in the working situation.

Motivation

Individuals not only differ greatly in basic abilities and skills, they evidence considerable variability in the degree to which these attributes are brought to bear upon the performance of a given task. Thus, of two subjects with test scores indicating equivalent skill levels, one will consistently outperform the other in a specific laboratory situation. Even if these hypothetical subjects were to perform equally well, the situation would still be far from satisfactory with regard to predicting their behavior in the "real world" for, as Trumbull (1965) has noted:

> The ability to translate...from academic tests of achievement or desire to achieve in an academic or test environment into the real world where real prices are paid for real errors still is to be demonstrated. Training or selection procedures which are tests of endurance in themselves, physical and stress, still enjoy a face validity, but the very essence of motivation continues to escape us (p. 41).

Certainly the "essence" has not escaped because of a lack of effort. Just as in the case of "personality," there is a voluminous body of literature dealing with the concept of "motivation." In his book on the psychology of learning, Deese (1958) expressed the opinion that:

> Discussion of the nature of human motivation has probably covered more paper than any other psychological topic. We must treat this vast literature rather cursorily, for the simple reason that not very much of it is relevant to the question of the relationship between motivation and learning (pp. 113-114).

With regard to the experimental study of human motivation, it is worthwhile to list the following points made by Deese (1958, p. 115) which include a broad definition of the concept itself (point number one):

1. Motivation-needs or drives-provides the internal impetus behind behavior and the direction which behavior takes - goals.

2. Motivation is an invented concept used to describe certain important things about animal and human behavior; it is not a fact of the world or an experimental variable that can be directly controlled and manipulated.

3. In the study of human motivation we are much more limited in the factors associated with motivation that we can manipulate directly.

4. It is extremely difficult to produce conditions in the experimental laboratory that allow systematic variation of these factors associated with human motivation.

In addition to being hard to handle experimentally, the concept of motivation appears difficult to separate from other factors which contribute to changes in performance. Emotional responses to environmental conditions perceived as "stressful" by subjects can interact with both the ability and the motivation to perform. Deese summarizes this interaction as follows:

> "...stress means heightened motivation as well as heightened emotional activity. What is more, in experimental studies of human behavior it is practically impossible to produce emotional disturbance without also producing a change in motivation (Lazarus, Deese, & Osler, 1952). Thus we cannot examine the effects of emotional arousal upon learning and performance without taking into consideration the effects of change in motivation (pp. 147-148).

Keeping in mind the general difficulties involved with the concept, let us now examine two recent attempts to delineate the effects of motivation on behavior under heat stress. The first study, and potentially the most important by virtue of its broader treatment of theoretical issues, is that by Teichner (1967). He begins by stating:

> All things considered, the problem of assessing human subjective thermal responses appears to have suffered from: (1) lack of use of psychophysical technique, that is methodology which relates behavior to physical or bodily conditions; (2) lack of a systematic, theoretical approach to guide research and define validity, and finally, to be discussed below, (3) failure to consider motivation as a factor in the human response (p. 502).

In outlining his approach, Teichner again underlines the role of motivation:

> In reviewing the various attempts that have been made to assess the human response to the thermal environment, it appears that two broad classes of response have been studied. On the one hand tolerance has been studied, largely as a physiological problem. On the other hand, subjective attitudes have been studied, largely by means of rating scales. It is of interest that both terms tend to suggest a motivational component and, in fact, it is commonplace in discussions of these topics for it to be noted that both tolerance (endurance time) and subjective rating depend upon the degree to which the subject is motivated to expose himself to the environment. Highly motivated subjects are assumed to tolerate more and have a wider comfort range than less highly motivated subjects. Invariably, discussion of this topic leads to commiserations about our inability to control this factor. The point of the present scaling approach is that it may not only be necessary to control motivation, but that a way must be found to incorporate it into a psychophysical testing procedure as a scale factor (p. 502).

Although space limitations preclude a detailed discussion of Teichner's approach, his major working postulate and its corollaries are listed below:

Basic postulate:

The length of time that an individual will voluntarily continue an exposure, represented by any given body state, is directly related to the magnitude of the reward he expects to receive for doing so. The function is asymptotic to some limiting voluntary tolerance time. (p. 502).

Corollary 1: In the absence of reward, no constant body state is tolerable for more than some maximum time (p. 502).

Corollary 1-a: In the absence of reward, the maximum voluntary thermal exposure time to any set of constant (non-noxious) conditions closely approximates the time required for the body to come into balance with the thermal environment (p. 503).

Corollary 2: In the absence of expected reward, the maximum thermal exposure time closely approximates the time required to feel discomfort or pain (p. 503).

Corollary 1 has practical as well as theoretical importance since it implies that there is no optimum or ideal fixed set of physiological conditions. Rather, ideal conditions are conceived of in terms of optimally varying physiological levels. Hence, the ideal thermal environment may not require the provision of some constant arrangement of air temperature, ventilation, humidity and radiation; instead, the thermal environment may consist of some optimally programmed arrangement of these variables. It is conceivable that if this line of reasoning is applied to the design and control of crew-station thermal environments, then suggestions for air-conditioning will no longer invoke instant rejection. In the case of rotary-wing aircraft, for example, where weight considerations are crucial, air-conditioning could be translated in its boradest sense, i.e., it would no longer impose a instant requirement for equipment capable of maintaining the cockpit temperature at 70°F, 60% R.H. under any external ambient temperature. Instead, smaller units could be planned with a view to periodic cooling and/or dehumidifying to achieve, over time, the program of environmental variation implied in Corollary 1.

In addition to the major premise and its corrolaries, Teichner has made other assumptions in his Approach:

1. The reduction or avoidance or escape from punishment is rewarding.

2. The nature and magnitudes of reward can be approached, at least for the present, in a "crude common sense way."

Referring to Figure 2, reproduced in its entirety from Teichner (1967, p. 503) some additional assumptions include:

3. Each bodily state has a certain amount of "utility" to the individual which can be expressed in terms of a trade-off between exposure time and reward.

4. With increasing deviations from the optimal zone level, the amount of utility decreases rapidly, probably in an exponential fashion.

5. For each curve there is a reward magnitude beyond which greater rewards fail to measurably increase voluntary exposure times.

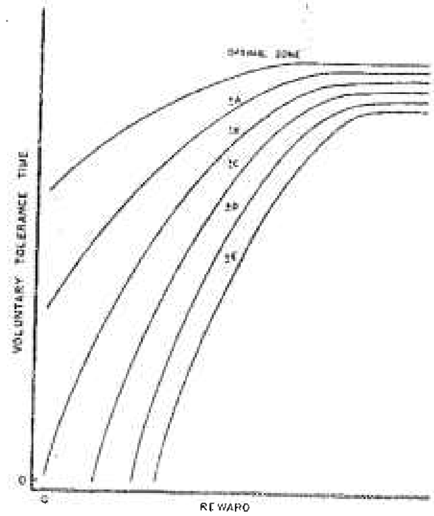

Fig. 2. THEORETICAL TRADE-OFF BETWEEN VOLUNTARY TOLERANCE TIME AND REWARD MAGNITUDE OF DIFFERENT, CONSTANT RANGES OF BODILY STATES; EACH BODILY STATE IS ASSUMED TO REPRESENT A CONSTANT "UTILITY" TO THE INDIVIDUAL (Labels ±A, ±B etc. represent deviations in either heating or cooling from the optimal zone.)

6. The individual will expose himself for some limited period of time even when reward is absent.

7. As "utility" of bodily state (physiological adjustment) decreases, there is some minimum or threshold reward required to increase voluntary tolerance time.

8. As reward magnitude increases beyond the threshold value, voluntary tolerance time increases rapidly to its maximum.

9. For any single curve, a really constant bodily state loses "utility" overtime, i.e., maintenance of a constant utility requires a fluctuating bodily state within the range or zone of such states represented by the curve.

That Teichner is aware of the many problems as well as the potential usefulness of the method outlined is evidenced by his own summary:

> Our approach requires a considerable amount of sophisticated research to give it more than formal appeal. Its great advantage is that it suggests a systematic way to approach

research on the problem and that in the absence of data it provides conceptual relationships which appear to agree with common experience with thermal feelings. In particular it has the advantage of introducing motivation as an integral, and we believe, workable, concept into a system which also incorporates other psychological concepts as well as physiological ones. However; it is recognized that reward is an elusive idea and that it may be necessary to have families of such indifference maps representing different kinds of rewards for a population or the same reward for different populations. Ultimately, perhaps, it will be possible to scale rewards so as to attain equivalences among different kinds or populations (p. 504).

A second and more recent experiment by London, Ogle, and Unikel (1968) examined the effects of motivating instructions and hypnotic susceptibility on continuous performance under heat stress. The authors summarize their findings as follows:

This paper reports an experiment which examined the relative effects of hypnosis, exhortative instructions, and routine task-performance instructions on the performance which individuals who differed in their degree of hypnotic susceptibility rendered on a continuous performance task both under normal conditions and under conditions of induced stress. High-susceptible (T) and low-susceptible (UT) Ss operated a pursuit rotor at room temperature and then under extreme heat. Performance of all Ss under stress improved after they were either hypnotized or exhorted to perform better; exhortion had a slightly but nonsignificantly greater effect (p. 532).

The study is considered here simply as an example of one obvious but often ignored method of eliciting motivated performance from subjects, viz. exhortation. The success of exhortative instructions is, of course, dependent on the relationship established between the experimenter(s) and the subject(s). Other techniques for increasing motivation include:

1. Knowledge of results (KR)–providing the subject with information which allows him to evaluate his performance in comparison with:

a. His previous level of performance.

b. Some maximum possible performance.

c. The performance of other subjects.

2. Provision of response contingent reinforcement–may include avoidance or removal of an aversive stimulus as well as availability of positive, desirable (to the subject) reward.

3. Use of experimental tasks the performance of which is in itself stimulating, interesting and rewarding.

Until such time as broad, theoretical systems such as that outlined by Teichner have received greater empirical validation, thermal-stress researchers will probably have to utilize some variation of the techniques suggested here to control for the effects of motivation.

GENERAL COMMENT ON SUBJECTS IN PSYCHOLOGICAL RESEARCH

It is desirable in any study, whether it involves thermal stress or not, that subjects perform in a highly motivated way, without displaying "undesirable" personality characteristics, and in a manner indicating maximum application of their skills and abilities. To achieve this goal, however, has proven difficult. Recently, articles have begun to appear which indicate that the problem may be a function of the overall philosophy of current psychological research. Schultz (1969) has written an excellent review of the factors involved, and sums up the problem by noting:

> In recent years, a number of psychologists have focused their research attention on the fundamental technique of their science: the experimental method. Articles and books have told us of experimenter effects in behavioral research (Rosenthal, 1966), the social nature of psychological research (Friedman, 1967), demand characteristics (Orne, 1962), and a host of other variables that may be confounding the data we continue to collect in such large quantities. We are warned, by the findings of this research on research, of the effect of unintended cues provided by our behavior, dress, speech, and commitment to a specific hypothesis; by the physical appearance of our laboratories; and by the general level of psychological research sophistication of the students who serve as our subjects. In short, this research suggests that the experimental situation may not be what we intend in our elaborately designed studies (p. 214).

What, if anything, can be done? Schultz lists two possible changes in basic procedures:

> 1. One approach, suggested by Brown (1965) and Kelman (1967), among others, is that of role playing. Instead of deliberately concealing the nature and purpose of the experiment, these would be explained to the subject and his cooperation sought. The intent is for the subject to directly and actively involve himself in the experiment, and to conscientiously participate in the experimental task. In this approach, the subject hopefully would have a more positive attitude toward the experiment and the experimenter if he felt that he was sharing with the experimenter in a collaborative endeaver rather than being used as a guinea pig (p. 226).
>
> 2. Another approach, suggested by Jourard (1968), involves the conducting of experiments with a mutual self-disclosure between the experimenter and the subject. Instead of the impersonal, detached and distrustful relationship that is now often the case, Jourard suggests a greater openness and mutual knowing in the experimenter-subject dyad. The subject would be encouraged to report what the stimuli and his behavioral responses really mean to him. The experimenter, in turn, would explain what he thinks the subject's responses mean, and the subject asked to respond. Thus, both experimenter and subject would be open and revealing to one another (p. 227).

These approaches appear particularly relevant to stress research for two reasons. First, subjects are frequently asked to perform under conditions which approach the limits of physiological tolerance. It seems probable that, in this situation, maximum continued performance depends on the subjects' confidence in the experimenter's ability to insure their physical safety as well as their opinion of the importance of the research. Second, many stress studies utilize military personnel, and here the consequences of performance, as inferred by the subjects themselves, can strongly affect their performance. Thus, unless they are informed as to the nature of the experiment, its goals, methods and procedures, military subjects (non-volunteers) may envision their performance as contributing to everything from promotion to punishment and modify it accordingly.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The previous sections of this report have examined, often in considerable detail, the nature of the variables and methodologies involved in the investigation of thermal stress. A comprehensive evaluation of this research area was undertaken for a number of reasons.

First, as noted in the introduction, there is a need to answer specific questions regarding the effect of extreme cockpit temperatures on the performance of Army aviators flying rotary-wing aircraft. It is unfortunate, however, that such needs appear paramount only during times of crises. A history of thermal-stress research clearly indicates that the bulk of the work to date has been done under the impetus of combat requirements, and neither industry nor the various branches of the military have produced any sustained investigative effort in this area. Rumors and/or informal pilot complaints are difficult to document and, even where this has been done, what generally results is, at best, a modification of the ECS for a particular type of aircraft. The results of such an approach are reflected in the literature and, concerning the Army's problem, one is forced to conclude:

1. Existing data do not possess sufficient validity or reliability to allow prediction of the magnitude, direction or significance of performance decrement under thermal stress.

2. Since decrement cannot be accurately predicted (except at physiological tolerance limits), the Army will continue to experience difficulty in establishing firm design standards for crew-station thermal environments.

3. Prediction of performance decrement (or the lack of decrement) cannot be achieved without first establishing a systematic and comprehensive measurement program to determine the internal temperature, humidity and radiation levels for <u>all</u> Army aircraft under

   a. Varying ambient conditions.

   b. Differing equipment/personnel configurations.

   c. Anticipated mission flight regimes.

A second reason for looking at heat-stress research in detail is based on the assumption that basic problems in this area exist with regard to the investigation of other environmental stressors. For example, the same difficulty in selecting an stress index which accurately reflects the relative contribution of the major variables involved can be found in both thermal and vibration-stress research. In heat the problem is how much weight to give to dry bulb temperature, wet bulb temperature, radient heating, connective cooling, etc. In vibration, analogous variables are frequency, amplitude, direction of movement, damping, etc. The critique of heat-stress methodology was therefore structured throughout to include environmental and subject variables whose manipulation or control is important in the study of any environmental stressor. Some general conclusions about thermal-stress research follow from the critique:

1. There are a number of conflicting reports regarding the effects of thermal stress on performance.

2. The first source of conflict is the inability of researchers to agree upon what levels of temperature, humidity, radiation, etc., constitute a "thermal stress" condition. Different investigators employ different parameters or the same parameters with different weightings; in addition, they often use differing exposure times.

3. A second source of conflict arises out of poor or inadequate control of subject variables; incidental sampling results in performance comparisons, between groups or individuals who differ markedly in both physiological and psychological characteristics.

4. The concept of physiological adequacy continues to dominate research strategy. Consequently, the role of psychological variables in both adaptation to and performance under "stress" remains relatively unexplored. In an article on men under "stress," Fraser (1968) eloquently underlines this point:

> Clearly, a man has remarkable capacities for adaptation (see HUMAN PERFORMANCE, July 1966) and normally can be relied upon to adjust to any reasonable demands made of him. But today, men are making excursions into new and more hazardous environments and are operating machines so complex that the demands upon them approach the limits of their capacities. A man is under stress no matter whether he is a decision-maker in an information-processing system, the pilot of a space craft, or a diver deep in the sea. The man-machine system into which he is thrust exists within a complex of environmental variables--interacting with each other, with the man, with the machine, and with the system. No longer can we assume that the effects on man are simply physiological--or are psychological alone. These factors are so interwoven that they must be carefully understood before any specific man-machine design is begun (p. 38).

5. In the preceding four points, the term "stress" appears in quotation marks, a technique used to imply that a concept is either inaccurate, poorly defined, or ambiguous; all three categories apply to heat "stress." In the literature reviewed, "stress" is loosely used to describe a particular set of thermal conditions, a subject's physiological responses to those conditions, or sometimes both. Fraser (1968) refers to this problem by observing:

> There is probably no term common to the engineer, physician, life scientist, and the lay public at large, that is more frequently misinterpreted, according to one's background and experience, than the word "stress."
>
> To the clinician, human stress is a somewhat tenuous concept involving physical, occupational, and social factors, any or all of which may unite to produce fear, confusion, emotional tension, physical discomfort, reduced resistance to disease and illness, and other physiological and clinical disturbances. To the life scientist, as we shall see, stress is a more well-defined entity and represents the set of circumstances which tend to disturb homeostasis, or internal stability. To the lay public (and perhaps the clinical psychologist) stress has connotation of social and emotional disturbance and inappropriate reaction.
>
> To add to the potential confusion, however, stress in medical terminology is defined in terms of the changes it produces in the body. According to Dr. Hans Selye, the Canadian authority who originated much of the contemporary concept of human stress, the term "systemic stress" is used to denote a condition in which extensive regions of the

body deviate from their normal resting state because of functional change or damage. In engineering terminology–stress can be inferred when strain is apparent (p. 39).

6. An elaboration of the preceding statement leads to a sixth conclusion in this section, viz. stress is an inferred state regardless of the accuracy with which one measures physiological changes occurring concomittently with changes in the thermal environment. Again, Fraser summarizes the point:

> If human response to environmental stress within the man-machine environmental complex exhibits both specific and nonspecific reactions which maintain homeostasis in the face of an immediate threat and mobilize the general body resources, how can the human response to stress be measured? To the engineer, the measurement of a stress/strain relationship can be relatively easy in many situations. The life scientist may be able to measure the magnitude of the stressors–if he can identify them. But stressors are multiple, frequently intangible, and the degree of the multiple responses cannot be predicted accurately because of the biological variability inherent in the individuals exposed.
>
> Thus presence of stress can only be inferred from observing the existence of strain, manifested as some kind of alteration in the normal pattern of human activity, whether it be change in capacity to do a task, change in behavior, or change in physiological function (p. 43).

The third reason for analysing thermal-stress research in depth centers about the problem of multiple-stressor effects on complex performances. The rationale underlying this report's approach is based in part on the assumption that the better our understanding of the effects of a single stressor the greater the likelihood of evaluating its contribution, antagonistic or synergestic, when it acts in concert with other stressors. Wilkinson (1969) after reviewing some of the literature on multiple-stressor effects, states:

> In terms of performance, it is the exception rather than the rule for the effects of single stresses to combine additively when they occur together. They may combine synergistically, as in the case of sleep deprivation and high doses of alcohol, or they may oppose each others' effects as in the case of sleep deprivation and noise. Much may depend upon the level or degree of the stress. Both heat and alcohol may combine synergistically with another stress (e.g., sleep deprivation) at one level and antagonistically at another (p. 270).

He continues,

> It is at a point as this that we come to realize the diversity, indeed the enormity, of this problem of predicting performance change as a function of environmental stress. There are so many extraneous factors which may combine in no simple way to decide the ultimate effect of a stress upon performance. In the short term, the very complexity of the picture that arises before us may argue the case for strictly ad hoc experiments, designed to provide a specific answer for a specific question–how much will performance be debased by this particular combination of stress and task conditions. For such work, the evidence reviewed in this report may be useful in underlining those aspects of the total working situation which must be simulated with reasonable accuracy if useful answers are to be derived. In the long term, however, the hope must be that the evidence from continued fundamental work, together with that from ad hoc experiments which can find time to run control groups, will amount to a set principles for at least broad prediction without resort to costly simulation (p. 271).

While it is possible to agree in principle with Wilkinson, the "state-of-the-art" in thermal-stress research prompts the following modifications of his conclusions:

1. The distinction between "fundamental work" and ad hoc experiments is somewhat spurious, at least in heat-stress research. As mentioned earlier, the majority of studies in this area are initiated in direct response to specific requirements generated by specific man-machine systems interacting with specific environments.

2. "Broad prediction" without simulation may not be possible in the light of the increasing complexity of man-machine systems. Alluise (1967), in discussing methodological issues in the use of synthetic tasks to assess complex performance, has concluded:

> The problems of performance assessment are obviously complex; but they are not impossible to solve. We believe it to be of great importance to the Department of Defense, to the field of human factors engineering, and to the entire science of psychology that concentrated efforts be made towards the solution of these problems. We believe that the most fruitful approach is one that studies man's performances of the functions typically required of him in any man-machine system, and one that studies these performances under controlled laboratory conditions, not only in isolation, but also in the complex combinations of multiple-task performance batteries.

3. Not all researchers are convinced that laboratory experiments can or will provide all the answers desired. Chapanis (1967), for example, summarizes the shortcomings of the approach:

> By their very nature laboratory experiments are at best only rough and approximate models of any real-life situation. First of all the possible independent variables that influence behaviour in any practical situation, a laboratory experiment selects only a few for test. As a result, hidden or unsuspected interactions in real-life may easily nullify, or even reverse, conclusions arrived at in the laboratory. Second, variables always change when they are brought into the laboratory. Third, the effect of controlling extraneous or irrelevant variables in the laboratory is to increase the precision of an experiment but at the risk of discovering effects so small that they are of no practical importance. Fourth, the dependent variables (or criteria) used in laboratory experiments are variables of convenience. Rarely are they selected for their relevance to some practical situation. Last, the methods used to present variables in the laboratory are sometimes artificial and unrealistic. The safest and most honest conclusion to draw from all these considerations is that one should generalize with extreme caution from the results of laboratory experiments to the solution of practical problems (p. 557).

While the risks cited above can never be completely eliminated from the laboratory approach, they can be minimized. It is hoped that this report will aid to some extent in the minimization process by identifying relevant variables as opposed to the "variables of convenience" referred to by Chapanis.

RECOMMENDATIONS

The recommendations for future research on thermal stress are, in most cases, implicit in the conclusions of the preceding section, and have appeared elsewhere in condensed form (Jones, 1969). For clarity, the recommendations follow the order used in the conclusions section i.e., recommendations first for the Army, next for thermal stress in general and, finally, for multiple-stressor research.

Army Aviation

The major need here is to establish a systematic, comprehensive program to measure the crew-station thermal environment for all Army aircraft in the current inventory. In addition, measurement procedures should be standardized to allow evaluation of new or proposed aircraft. The program must include dry bulb, wet bulb, air velocity and radiation measurements of crew-stations, taking into consideration the following factors:

1. Ambient Temperature and Humidity--Internal aircraft temperatures should be measured under the extreme climatic conditions listed in AR 70-38 (Headquarters, Department of the Army, 1969), both with and without the environmental control system in operation. The placement of temperature, humidity, and radiation sensors could follow the general procedure outlined in section 3.11.8.1.1 of MIL-I-5289B (U. S. Air Force, 1954).

2. Equipment/Crew Configurations--Cockpit heat loads will vary as a function of the number and type of avionic systems employed, operator clothing and specialized combat equipment worn, aircrew seat configurations, etc. Because of the number of possible permutations of clothing and equipment it may be necessary, in the early stages of the measurement program, to select "generic" configurations, i.e., crew wearing standard nomex flight clothing, with armored vests, sitting in armored seats and operating specific avionic and weapons subsystems for fixed periods of time.

3. Mission Flight Regimes--Even with "standard" clothing and equipment specified, the crew-station thermal environment can vary in response to mission parameters such as altitude and speed as well as the length of the mission itself. Here again it may be necessary to examine a limited number of mission profiles, each of which embodies a variable of interest. For example, low-level, low-speed conditions should certainly be represented because of the potential "greenhouse effect" attributable to large amounts of reflected solar radiation impinging on pilot and aircraft.

Thermal Stress Research

1. The first requirement is the adoption of a standardized index which will represent those components of the thermal environment which act to produce what is often referred to simply as "heat." This report has suggested the WBGT index since it provides index values which incorporate wet and dry bulb temperatures (and hence humidity) plus black globe integration of radiant heating and convective cooling (eliminating the need for air velocity measures). The WBGT index would allow more accurate comparisons to be made between research findings because investigators would be required to report the actual component values as well as the weighted summation according to the formula $WBGT = .7WB + .2GT + .1DB$.

2. Assuming that a standard index had been agreed upon, the next step is to compile probability curves for the joint occurrence of the variables involved in the hottest portions of the world, during the hottest months. The Air Force has done this for wet and dry bulb temperatures and efforts should be made now to include solar radiation levels. The extreme points on the three-variable curves should then become design guides for aircraft crew-station environmental control systems.

3. Given a standardized index and a knowledge of those thermal conditions expected to obtain in the predicted operational environment for a given man-machine system, laboratory research should be undertaken which incorporates the following:

a. A shift in emphasis from "stress" to "strain" in which the impact of the thermal environment is considered "stressful" only to the extent that it is correlated with significant changes in an individual's ability to perform a given task. A causal orientation has resulted in overemphasis on physiological adaptation mechanisms, frequently to the exclusion of other potentially important variables. In addition, this orientation has led to the tacit acceptance of the "concept of physiological adequacy," a concept it is time to question experimentally. It should no longer be assumed that human performance under conditions of high ambient temperature and humidity will remain "normal" as long as physiological adaptation is maintained.

b. Greater emphasis on psychological variables such as learning, motivation and personality as they interact with both environmental and task variables.

c. Increased attention to the kinds of complex performance demanded of the human operator in modern man-machine systems.

4. Once research begins to focus on the effects of the thermal environment on operators performing complex, continuous tasks involving memory, judgment, time sharing, etc., then the subject variables treated in the previous sections of this report become quite important. The physiological, physical and psychological makeup of subjects, acting singly or in groups, must be controlled for. Such control involves increased precision in experimental designs and sampling techniques. Incidental sampling and very small samples should be avoided in the early stages of thermal-stress research.

Multiple Stressor Research

All the preceding recommendations apply, particularly the one dealing with experimental control. Indeed, the establishment of valid and reliable physiological and psychological "norms" is a major problem in any environmental research. What is needed is a program similar to that suggested by Rohles (1965) which aims at defining the "Standard Man." A tentative list of the conditions necessary for the Standard Man measurements appears in Table 14 (reproduced in its entirety from Rohles, 1965).

TABLE 14

Conditions for Making the Standard Man Measurements

A. PHYSICAL	
1. Temperature	$80^{\circ}F$ (Air temperature and mean radiant temperature equal)
2. Humidity	50%
3. Force Field	1 G
4. Air Movement	Less than 45 fpm
5. Atmospheric Pressure	14.7 psia (sea level)
6. Inspired Gas	Filtered, odorless, air (21% O_2; 78% N)
7. Radiation	Not to exceed AEC minimums
8. Area-Volume	To be specified
9. Light	20-50 ft. candles (Room color: White)
10. Sound	Not to exceed 50 db
B. ORGANISMIC	
1. Subject	Male, mesomorph, single, native to locale; sample size; not less than 300
2. Age	21 years
3. Diet	At least 5 days at 3000 cal/day
4. Rhymicity	All tests at same time of day and year
5. BMR	37-40 Cal m^2 body surface/hr
C. RECIPROCATIVE	
1. Activity	Lying down or seated
2. Clothing	Nude
3. Exposure Time	To be specified
4. Social	10 subjects per test group

Rohles describes the program as follows:

Briefly the Standard Man would define the limits of physiological and psychological functioning under a non-stressful, anoxious, and neutral environment. Then when research in stressful environments is conducted, the extent of deviation from the Standard Man could be determined, and would indicate the effect of the altered environment on the particular measure in question. The mechanics for collecting the normative data for the Standard Man would have to be placed in the hands of an interdisciplinary committee composed of physiologists, psychologists, engineers, physicians, and biochemists. First they would have to enumerate the measures necessary to determine the physical or psychological functioning of the subject. For the physician and physiologist, these would include body temperature, cardiac functioning, respiration, and galvanic skin response, to name a few. Blood and urine measurements would be of interest to the biochemist, and the psychologist would include finger and manual dexterity, reaction time, tracking, monitoring and intellectual tasks. Once

these measures had been selected they would be taken in a neutral environment, taking into account the physical, organismic, and reciprocative factors noted above.

A program of this scope and magnitude would necessarily be expensive and time-consuming. It is the opinion of this author, however, that the predictive validity of environmental stress research will ultimately depend upon the existence of the kind of normative data generated by such a program.

REFERENCES

1. Allan, J. R. The effects of physical training in a temperate and hot climate on the physiological responses to heat stress. Ergonomics, 1965, 4, 445-453.

2. Allan, J. R., Beeston, D. T., Crowdy, J. P., Haisman, M. F., Peters, D. W. A., & Zurick, L. Initial experiments on the induction and maintenance of artificial acclimatization. Army Operational Research Establishment Report No. 12/63, 1963.

3. Alluisi, E. A. Methodology in the use of synthetic tasks to assess complex performance. Human Factors, 1967, 9, 375-384.

4. Anderson, P. F. AH-1G '90 days in RVN' - An analysis of the aircraft AH-1G NETT. 1967.

5. Argyris, C. Some unintended consequences of rigorous research. Psychological Bulletin, 1968, 70, 185-197.

6. Aschoff, J., & Wever, R. Naturwissenschaft, 1962, 15, 337.

7. ASHRAE Guide and Data Book: Fundamentals and equipment for 1965 and 1966. New York: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1965.

8. Balke, B., & Ware, R. W. An experimental study of 'physical fitness' of Air Force personnel. U. S. Armed Forces Medical Journal, 1959, 10, 675-688.

9. Bartlett, D. J., & Gronow, D. G. C. The effects of heat stress on mental performance. Flying Personnel Research Committee Report 846, 1953, England, 1-16.

10. Bedford, T. Researches on thermal comfort. Ergonomics, 1961, 4, 289-310.

11. Belding, H. S., & Hatch, T. F. Index for evaluating heat stress in terms of resulting physiologic strains. Heating, Piping and Air Conditioning, 1955, 129.

12. Bell, C. R. Time estimation and increases in body temperature. Journal of Experimental Psychology, 1965, 70, 232-234.

13. Bell, C. R., & Provins, K. A. Effects of high temperature environmental conditions on human performance. Journal of Occupational Medicien, 1962, 4, 202-221.

14. Bell, C. R., Provins, K. A., & Hiorns, R. W. Visual and auditory vigilance during exposure to hot and humid conditions. Ergonomics, 1964, 7, 279-288.

15. Billings, C. E., Eggspuehler, J. J., Gerke, R. J., & Chase, R. C. Studies of pilot performance: II. Evaluation of performance during low altitude flight in helicopters. Aerospace Medicine, 1968, 39, 19-31.

16. Bills, A. G. The psychology of efficiency. New York: Harper & Brothers, 1943.

17. Blockley, W. V., & Lyman, J. Studies of human tolerance for extreme heat. III. Mental performance under heat stress as indicated by addition and number checking tests. Air Force Technical Report No. 6022, Air Materiel Command, Wright-Patterson AFB, Ohio, 1950.

18. Blockley, W. V., & Lyman, J. Studies of human tolerance for extreme heat. IV. Psychomotor performance of pilots as indicated by a task simulating aircraft instrument flight. Wright Air Development Center Technical Report No. 6521, Wright-Patterson AFB, Ohio, 1951.

19. Blockley, W. V., McCutchan, J. W., & Taylor, C. L. Prediction of human tolerance for heat in aircraft: A design guide. Wright Air Development Center Report No. 53-346, Wright-Patterson AFB, Ohio, 1954.

20. Blyth, C. S., & Lovingood, B. W. Psychomotor responses and their relationship to personality traits of young men performing in high ambient temperature (110 F) Research Quarterly, 1964, 35, 241-245.

21. Brown, R. Social psychology. New York: Free Press, 1965.

22. Bursill, A. E. The restriction of peripheral vision during exposure to hot and humid conditions. Quarterly Journal of Experimental Psychology, 1958, 10, 113-129.

23. Carlson, L. D. Human performance under different thermal loads. USAF Aerospace Medical Center, School of Aviation Medicine Report No. 61-43, Brooks AFB, Texas, 1961.

24. Chapanis, A. The relevance of laboratory studies to practical situations. Ergonomics, 1967, 10, 557-577.

25. Chiles, W. D. Effects of elevated temperatures on performance of a complex mental task. Ergonomics, 1958, 2, 89-96.

26. Chiles, W. D. Effects of high temperatures on performance of a complex mental task. Wright Air Development Center Technical Report 58-323, Wright-Patterson AFB, Ohio, 1958.

27. Coakley, J. D. The effect of ambient and body temperatures upon reaction time. Psychological Corporation Report No. 151-1-13, New York, 1948.

28. Collins, K. J., & Weiner, J. S. Endocrinological aspects of exposure to high environmental temperatures. Physiological Reviews, 1968, 48, 785-839.

29. Colquhoun, W. P. Temperament, inspection efficiency, and time of day. Ergonomics, 1960, 3, 377-378.

30. Connell, L. The effect of heat upon the performance of men in high-speed aircraft: A critical review. Special Devices Center Report 151-1-17, Office of Naval Research, Washington, D. C., 1948.

31. Craig, F. N. Ventilation requirements of an impermeable protective suit. Medical Division Research Report No. 5, Chemical Corps, Army Chemical Center, April 1950.

32. Davis, H. T., & Kaufman, W. C. Experimental determination of the maximum safe thermal radiation loads for a fighter-bomber cockpit. Aerospace Medical Research Laboratories Technical Report 64-139, Wright-Patterson AFB, Ohio, 1964.

33. Deese, J. The psychology of learning. New York: McGraw-Hill, 1958.

34. Engleman, T. G., & Kleitman, N. Journal of Applied Physiology, 1953, 6, 269.

35. Environmental Protection Division. Environment of Southeast Asia. Report No. 219, Natick QM Research & Development Laboratory, 1953.

36. Fine, B. J. The comparative effectiveness of some psychological and physiological measures in ranking the impact of diverse environmental conditions. Journal of Applied Psychology, 1958, 42, 353-356.

37. Fine, B. J., Cohen, A., & Crist, B. The effect of exposure to high humidity at high and moderate ambient temperatures on anagram solution and auditory discrimination. Psychological Reports, 1960, 7, 171-181.

38. Fleishman, E. A. Human abilities and the acquisition of skill. In E. A. Bilodeau (Ed.), Acquisition of skill. New York: Academic Press, 1966. Pp. 147-167.

39. Fleishman, E. A. The structure and measurement of physical fitness. Englewood Cliffs, N. J.: Prentice Hall, 1964.

40. Fox, R. H. Heat. In O. G. Edholm & A. L. Bacharach (Eds.), The physiology of human survival. New York: Academic Press, 1965. Pp. 53-79.

41. Fox, R. H., Bradbury, P. A., Hampton, I. F G., & Legg, C. F. Time judgment and body temperature. Journal of Experimental Psychology, 1967, 75, 88-96.

42. Fraser, D. C., & Jackson, K. F. Effect of heat stress on serial reaction time in man. Nature, 1955, 176, 976-977.

43. Fraser, T. M. Men under stress. Science & Technology, January 1968, 38-44.

44. Frazier, T. W., Rummel, J. A., & Lipscomb, H. S. Circadian variability in vigilance performance. Aerospace Medicine, 1968, 39, 383-395.

45. Friedman, N. The social nature of psychological research. New York: Basic Books, 1967.

46. Gagne, R. M., & Fleishman, E. A. Psychology and human performance: An introduction to psychology. New York: Holt, 1959.

47. Gelineo, S. Organ systems in adaptation: The temperature regulating system. In D. B. Dill, E. F. Adolph, & C. G. Wilber (Eds.), Handbook of physiology. Washington, D. C.: The American Physiological Society, 1964. Pp. 259-282.

48. Givoni, B., & Rim, Y. Effect of the thermal environment and psychological factors upon subjects' responses and performance of mental work. Ergonomics, 1962, 5, 99-114.

49. Glaser, E. M. Acclimization to heat and cold. Journal of Physiology, 1949, 110, 330-337.

50. Gold, J. Calorie neutralization during thermal stress. Aerospace Medicine, 1960, 31, 933-940.

51. Gold, J. Development of heat pyrexia. Journal of the American Medical Association, 1960, 173, 1175-1182.

52. Gold, J. A unified system for evaluation and selection of heat stress candidates. Journal of Applied Physiology, 1961, 16, 144-152.

53. Goldsmith, R., Fox, R. H., & Hampton, I. F. G. Effects of drugs on heat acclimization by controlled hypersthermia. Journal of Applied Physiology, 1967, 22, 301-304.

54. Grandjean, E. Fatigue: Its physiological and psychological significance. Ergonomics, 1968, 11, 427-436.

55. Groth, H., & Lyman, J. Measurement methodology for perceptual-motor performance under highly transient extreme heat stress. Human Factors, 1963, 391-403.

56. Guilford, J. P. Fundamental statistics in psychology and education. New York: McGraw-Hill, 1965.

57. Hale, H. B., & Shannon, I. L. Validity of the human 17-hydroxycorticosteroid/creatinine ratio. Aerospace Medicine, 1967, 38, 1095-1098.

58. Hall, J. F. & Polte, J. W. Physiological index of strain and body heat storage in hyperthermia. WADD Technical Report 60-599, Wright-Patterson AFB, Ohio, 1961.

59. Hendler, E. Temperature effects on operator performance. In N. M. Burns, et al., (Eds.), Unusual environments and human behavior. London: Free Press, 1963.

60. Iberall, A. S., & Cardon, S. Z. Analysis of the dynamic systems response of some internal human systems. NASA contractor report NASA CR-141, General Technical Services, Inc., Clevaland, Ohio, 1965.

61. Jones, R. D. Psychomotor performance under thermal stress: A critical appraisal. North Atlantic Treaty Organization, Advisory Group for Aerospace Research and Development, AGARD Conference Proceedings No. 56, 1969, 3-1, 3-14.

62. Jourard, S. M. Disclosing man to himself. Princeton, N. J.: Van Nostrand, 1968.

63. Joy, J. T. Heat stress in army pilots flying combat missions in the Mohawk aircraft in Vietnam. Aerospace Medicine, 1967, 895-900.

64. Kaufman, W. C. Human tolerance limits for some thermal environments of aerospace. Aerospace Medicine, 1963, 34, 889-896.

65. Kelman, H. C. Human use of human subjects: The problem of deception in social psychological experiments. Psychological Bulletin, 1967, 67, 1-11.

66. Kleber, R. J., Lhamon, W. T., & Goldstone, S. Hyperthermia, hyperthyroidism and time judgment. Journal of Comparative and Physiological Psychology, 1963, 56, 362-365.

67. Ladell, W. S. S. Terrestrial animals in humid heat: Man. In D. B. Dill, E. F Adolph, & C. G. Wilber (Eds.), Handbook of physiology. Washington, D. C.: The American Physiological Society, 1964. Pp. 625-659.

68. Lee, D. H. K. Terrestrial animals in dry heat: Man in the desert. In D. B. Dill, E. F. Adolph, & C. G. Wilber (Eds.), Handbook of physiology, 1964. Pp. 551-582.

69. Lewis, P. R., & Loban, M. C. Dissociation of diurnal rhythms in human subjects living on abnormal time routines. Quarterly Journal of Experimental Physiology, 1957, 42, 371-386.

70. Loban, M. C. Dissociation in human rhythmic functions. In J. Aschoff (Ed.), Circadian clocks. Amsterdam: North-Holland Publishing Co., 1965.

71. Loeb, M., Jeantheau, G., & Weaver, L. A. A field study of a vigilance task. Army Medical Research Laboratory Report No. 230, Fort Knox, Ky., 1956.

72. London, P., Ogle, M. E., & Unikel, I. P. Effects of hypnosis and motivation on resistance to heat stress. Journal of Abnormal Psychology, 1968, 73, 532-541.

73. Lovingood, B. W., Blyth, C. S., Peacock, W. H., & Lindsay, R. B. Effects of d-amphetamine sulfate, caffeine, and high temperature on human performance. Research Quarterly, 1967, 38, 64-71.

74. McDonald, J. L. A review of high temperature extremes in AR 705-15 and MIL-STD 210A as compared with world wide weather data. USAERDL, Fort Belvoir, Va., 1964.

75. Mackworth, N. H. Effects of heat and high humidity on pursuitmeter scores. Report No. 45/199, Report to the Royal Naval Personnel Research Committee (Unpublished).

76. Mackworth, N. H. Effects of heat on wireless operators hearing and recording morse code messages. British Journal of Industrial Medicine, 1946a, 3, 143-157.

77. Mackworth, N. H. Effects of heat and high humidity on prolonged visual search as measured by the clock test. Report No. 46/278, Report to the Royal Naval Research Committee (Unpublished).

78. Mackworth, N. H. Researches on the measurement of human performance. In H. W. Sinaiko (Ed.), Selected papers on human factors in the design and use of control systems. New York: Dover Publications, 1961. Pp. 174-331.

79. Mandler, G., & Kessen, W. The language of psychology. New York: John Wiley & Sons, Inc., (Science editions), 1964.

80. Martorano, F. L. Report on ambient versus inside-vehicle weather conditions in South Vietnam relative to the humidity test of conventional ammunition for the Sheridan weapon system. Commodity Management Office, Picatinny Arsenal, Dover, N. J., 1966.

81. Mayo, G. D. Effect of temperature upon technical training. Journal of Applied Psychology, 1955, 39, 244-246.

82. Minard, D. Effective temperature scale and its modification. Report No. 6, Naval Medical Research Institute, Bethesda, Md., 1964.

83. Moreland, S., & Barnes, J. Exploratory study of pilot performance during high ambient temperatures/humidity. Technical Memorandum 6-70, Human Engineering Laboratories, USA Aberdeen Research & Development Center, Aberdeen Proving Ground, Md., 1970.

84. Morimoto, T., Slabochova, Z., Naman, R. K., & Sargent, F. Sex differences in physiological reactions to thermal stress. Journal of Applied Physiology, 1967, 22, 526-532.

85. Orne, M. T. On the social psychology of the psychological experiment: With particular reference to demand characteristics and their implications. American Psychologist, 1962, 17, 776-783.

86. Parker, J. F Use of an engineering analogy in the development of tests to predict tracking performance. The Matrix Corporation, Arlington, Va., 1964.

87. Peacock, L. J. A field study of rifle aiming steadiness and serial reaction performance as affected by thermal stress and activity. Army Medical Research Laboratory Report No. 231, Fort Knox, Ky., 1956.

88. Pepler, R. D. The effect of climatic factors on the performance of skilled tasks by young European men living in the tropics. APU Report Nos. 153, 154, 156, 196, 197, Medical Research Council, 1953.

89. Pepler, R. D. Warmth and performance: An investigation in the tropics. Ergonomics, 1958, 2, 63-88.

90. Pepler, R. D. Extreme warmth and sensorimotor coordination. Journal of Applied Physiology, 1959, 14, 383-386.

91. Pepler, R. D. Warmth, glare and a background of quiet speech: A comparison of their effects on performance. Ergonomics, 1960, 3, 68-73.

92. Peters, D. W. A. Report on a prototype wet bulb globe thermometer index meter for service use. Research Memorandum P/4, Army Personnel Research Establishment, 1967.

93. Poulton, E. C., & Kerslake, M. B. Initial stimulating effect of warmth upon perceptual efficiency. Aerospace Medicine, 1965, 29-32.

94. Pugh, L. G. C. E., Corbett, J. L., & Johnson, R. H. Rectal temperatures, weight losses, and sweat rates in marathon running. Journal of Applied Physiology, 1967, 23, 347-352.

95. Reilly, R. E., & Parker, J. F. Effect of heat stress and prolonged activity on perceptual-motor performance. NASA Contract No. 1329. Report prepared by Biotechnology, Inc., Arlington, Va., 1967.

96. Reilly, R. E., & Parker, J. F. Development of an improved perceptual-motor performance measurement system. Biotechnology, Inc., Arlington, Va., 1967b.

97. Robinson, S., Turrel, E. S., & Gerking, S. K. Physiologically equivalent conditions of air temperature and humidity. American Journal of Physiology, 1945, 143, 21.

98. Rohles, F. H. Consideration for environmental research in human factors. The Journal of Environmental Sciences, 1965, 8, 18-20.

99. Rohles, F. H., Nevins, R. G., & Springer, W. E. Temporal characteristics of body temperature during high thermal stress. Aerospace Medicine, 1967, 286-290.

100. Rosenthal, R. Experimenter effects in behavioral research. New York: Appleton-Century-Crofts, 1966.

101. Russell, R. W. Effects of variations in ambient temperature on certain measures of tracking skill and sensory sensitivity. Army Medical Research Laboratory Report No. 300, Fort Knox, Ky., 1957.

102. Schultz, D. P. The human subject in psychological research. Psychological Bulletin, 1969, 3, 214-228.

103. Simpson, H. W., & Loban, M. C. Effect of a 21-hour day on the human circadian excretory rhythms of 17-hydroxycorticosteroids and electrolytes. Aerospace Medicine, 1967, 12, 1205-1213.

104. Sunderman, F. W., & Boerner, F. Normal values in clinical medicine. Philadelphia: W. B. Saunders Co., 1949.

105. Taylor, C. L. Description and prediction of human response to aircraft thermal environments. ASME Aviation Division Report No. 56-AV-3, 1953.

106. Teichner, W. H. The subjective response to the thermal environment. Human Factors, 1967, 9, 497-510.

107. Teichner, W. H., & Wehrkamp, R. F. Visual-motor performance as a function of short-duration ambient temperature. Journal of Experimental Psychology, 1954, 47, 447-450.

108. Trumbull, R. Environment modification for human performance. Office of Naval Research Report ACR-105, Office of Naval Research, Washington, D. C., 1965.

109. U. S. Air Force. General specification for instrument installation for climatic test of aircraft. MIL-I-5289B(ASG), Military Specification, Wright-Patterson AFB, Ohio, 1954.

110. U. S. Army. Human reactions to high temperatures: Annotated bibliography (1927-1962). U. S. Army Tropic Test Center, Fort Clayton, Canal Zone, 1967.

111. U. S. Army. Research, development, test, and evaluation of materiel for extreme climatic conditions. Army Regulation 70-38. Headquarters, Department of the Army, Washington, D. C., 1969.

112. Vaughan, J. A., Higgins, E. A., & Funkhouser, G. E. Effects of body thermal state on manual performance. Aerospace Medicine, 1968, 39, 1310-1315.

113. Viteles, M. S., & Smith, K. R. An experimental investigation of the effect of change in atmospheric conditions and noise upon performance. Heating, Piping & Air Conditioning, ASHVE, 1946, 18, 107-112.

114. Watkins, E. S. The effect of heat on psychomotor efficiency, with particular reference to tropical man. Liverpool: M. D. Thesis, 1956.

115. Weiner, J. S., & Hutchinson, J. O. D. Hot humid environment: Its effect on the performance of a motor coordination task. British Journal of Industrial Medicine, 1945, 2, 154-157.

116. Weinman, K. P., Slabochova, Z., Bernauer, E. M., Morimoto, T., & Sargent, F. Reactions of men and women to repeated exposure to humid heat. Journal of Applied Physiology, 1967, 22, 533-538.

117. Welch, B. E. Caloric intake and energy expenditure of eleven men in a desert environment. Report No. 190, Project 6-60-11-020, Medical Nutrition Laboratory, Fitzsimmons Army Hospital, Denver, Colo., 1956.

118. Wilber, C. G. Water requirements of man. U. S. Armed Forces Medical Journal, 1957, 8, 1121-1130.

119. Wilkinson, R. Some factors influencing the effect of environmental stressors upon performance. Psychological Bulletin, 1969, 72, 260-272.

120. Wilkinson, R. T., Fox, R. H., Goldsmith, R., Hampton, I. F. G., & Lewis, H. E. Psychological and physiological responses to raised body temperature. Journal of Applied Physiology, 1964, 19, 287-291.

121. Wing, J., & Touchstone, R. M. A bibliography of the effects of temperature on human performance. Aerospace Medical Research Laboratories Technical Documentary Report 63-13, Wright-Patterson AFB, Ohio, 1963.

122. Wing, J. F. Upper thermal tolerance limits for unimpaired mental performance. Aerospace Medicine, 1965, 960-964.

123. Wing, J. F. A review of the effects of high ambient temperature on mental performance. Aerospace Medical Research Laboratories Technical Report 65-102, Wright-Patterson AFB, Ohio, 1965.

124. Wing, J. F., & Touchstone, R. M. The effects of high ambient temperature on short-term memory. Aerospace Medical Research Laboratories Technical Report 65-103, Wright-Patterson AFB, Ohio, 1965.

125. Wyndham, C. J., Bauwer, W., Devine, M. G., Patterson, H. E., & MacDonald, D. K. C. Examination of use of heat exchange equations for determining changes in body temperature. Journal of Applied Physiology, 1952, 5, 299.

126. Yaglou, C. P. Indices of comfort. In L. H. Newberg (Ed.), Physiology of heat regulation and science of clothing. Philadelphia: W. B. Saunders Co., 1949.

127. Yaglou, C. P., & Minard, D. AMA Archives of Industrial Health, 1957, 16, 302-316.

APPENDIX A

LITERATURE SUMMARY

PERFORMANCE MEASURED	EXPERIMENTAL TEMPERATURES			EXPOSURE TIMES		N	DIR OF PERF CHANGE			AUTHOR
SENSORY THRESHOLDS & REACTION TIMES	Dry Bulb °F	Wet Bulb °F	% Rel Hum	Hrs	Min		+	0	-	
Simple Reaction Time	126		25-40		210	24	X			Lovingood, et al, 1967
" "	100	80	(ET=86)	6		18	X			Reilly & Parker, 1967
Simple & Serial RT	86	86	100	6		8		X		Ivy, et al, 1944
" "	117	85	17	6		8		X		" "
" "	90	83		21		20		X		Pace, et al, 1945
" "	108	83		3		20		X		" "
Serial RT	92-104				2.5	14		X		Peacock, 1956
Tactile Sensitivity	104		30	Task Det.		72			X	Russell, 1957
Serial RT	90-104		90-95	1,2		7			X	Fraser & Jackson, 1955
VIGILANCE & PERCEPTION										
Spatial Orientation							X			
Visual Vigilance	100	80	(ET=86)	6		18	X			Reilly & Parker, 1967
Perceptual Speed							X			
Auditory & Visual Vig.	113		(ET=86)		20	12	X			Poulton, et al, 1965
Auditory Vigilance	Body Temp = 101°F				63	12	X			Wilkenson, et al, 1964
Visual Vigilance	100-115		4-24	4		12		X		Loeb, et al, 1956
" "	104, 122		20	1,2&3		9		X		Carlson, 1961
Auditory & Visual Vig.	85-145	76-117		1/3-4		8		X		Bell, et al, 1964
Auditory Discrim.	95	70,92		6 1/2		10		X		Fine, et al, 1960
Visual Vigilance	85	75	(ET 79)						X	Mackworth, 1946a,b
Auditory Vigilance			(ET79-97)						X	" 1961
Visual & Auditory Vig.			(ET81-86)						X	Pepler, 1958
Peripheral Vision	105	95	(BET 95)		140	18			X	Bursill, 1958

PERFORMANCE MEASURED	EXPERIMENTAL TEMPERATURES			EXPOSURE TIMES		N	DIR OF PERF CHANGE			AUTHOR
PSYCHOMOTOR	Dry Bulb ^{o}F	Wet Bulb^{o}F	% Rel Hum	Hrs	Min		+	0	-	
Rapid Line Drawing	115			2		36	X			Vaughan, et al, 1968
Mirror Tracing	100	80	(ET=86)	6		18	X			Reilly & Parker, 1967
Wrist-Finger Speed							X			
Hand-Finger Dexterity	126		25-40		210	24	X			Lovingood, et al, 1967
Muscular Control, Eye-								X		
Hand Coord, Pursuit &	100	80	(ET=86)	6		18		X		Reilly & Parker, 1967
Compensatory Tracking								X		
Pursuit Tracking	104		30	Task Det.		126		X		Russell, 1957
Arm-Hand Coord	126		25-40		210	24		X		Lovingood, et al, 1967
Pursuit Tracking	------- ET 86 --------								X	Mackworth, 1945, 1961
" "	------- ET 81-86 --------								X	Pepler, 1953, 1958, 1960
" "	116	105			30	6			X	" 1959
Simulator "Piloting"	160, 210, 235		20-30	Physiol Det		4			X	Blockley & Lyman, 1951
Time Sharing, Target Prediction	100	80	(ET=86)	6		18			X	Reilly & Parker, 1967
Rotary Pursuit Tracking									X	Teichner, et al, 1954
COMPLEX "MENTAL"										
Addition (no attempted)	126		25-40		210	24	X			Lovingood, et al, 1967
Anticipatory Perception Judgment	80, 90, 100	70, 80, 90			60	16		X		Bartlett, et al, 1955
Elec. Trng. Course	86-92					80		X		Mayo, 1955
Discrimination	85-100	75-90	(ET76-91)					X		Chiles, 1957
" "	85-110	75-90		1		10		X		" 1958
Anagram Solution	95	70, 92		6 1/2		10		X		Fine, et al, 1960
5 Digit Mult., IQ Test	109		40	2		4		X		Givoni & Rim, 1962
Discrimination	------ ET 76-91 -------								X	Pepler, 1958
Auditory Recall	------ ET 90, 95 -------			1		15			X	Wing, et al, 1965
No. Checking & Addition	160, 200, 235			Physiol Det		8			X	Blockley & Lyman, 1950
Simple Addition	Body Temp = 102^{o}F				63	12			X	Wilkenson, et al, 1964
Time Perception					45	12			X	Fox, et al, 1967

APPENDIX B

VARIABLES RELEVANT TO STRESS RESEARCH

ENVIRONMENTAL

Indices of Stress

ET	Effective Temp.	1923
ETC	Effective Temp. Corrected	1932
EP	Physiol. Effect	1945
CET	Corrected Effective Temp.	1946
C.I.	Craig Index of Strain	1950
ETR	Effective Temp. & Radiation	1950
P4SR	Four-Hour Sweat Rate	1952
HSI	Heat Stress Index	1955
WBGT	Wet Bulb Globe Temp.	1956

Source of Stressor

- Climatic Chamber vs. Outside Ambient Conditions

Exposure Times

- Single vs. Repeated
- Continuous vs. Intermittent

SUBJECT

Physiological

Adaptive System Responses
- Hypothalamic-regulatory
- Metabolic-endocrinological
- Cardiovascular
- Respiratory
- Heat Storage

Acclimatization

Circadian Rhythms

Physical

Age
Sex
Physique
Physical Condition
Nutritional State
Health - Present & Past History

Psychological

Personality
- Skills & Abilities
- Motivation

Intelligence

Response "Set"

Fatigue

TASK

Type
- Complex vs. Simple
- Novel vs. Repetitive
- Continuous vs. Discrete

Validity
- Lab vs. Operational Situation
- (Face vs. Construct Validity)

Instructions
- Written
- Demonstration
- Verbal

Learning Factors
- Feedback -- Continuous vs. Discrete
- Reinforcement --
  - Learning vs. Perf.
  - Extrinsic vs. Intrinsic
- Methods of Administration
  - Time, situation, physical environment
- Fatigue

Data Collection
- Measurement Scales
- Frequency of Measurements
  - Performance Averaging

Statistics
- Sampling --
  - Size - N = ?
  - Composition: random, stratified incidental
- Reliability -- normative data

Interactions
- Single vs. multivariate predictions
- Potentiation

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13. ABSTRACT

A critical review of the literature provides the basis for an analysis of the effects of thermal stress on human performance. Research in this area to date reflects a wide divergence of opinion regarding the magnitude, direction and significance of performance changes occurring under conditions of high temperature, humidity, solar radiation, etc. An attempt to resolve major conflicts in experimental findings leads to a detailed examination of such factors as thermal stress indices, exposure times and acclimatization. The role of the subject in thermal stress research is discussed with emphasis on the contribution of such psychological variables as personality and motivation to performance change. Recommendations for future research are advanced.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Thermal Stress						
Human Performance						
Psychomotor Performance						
Crew Station Environment						
Human Factors Engineering						